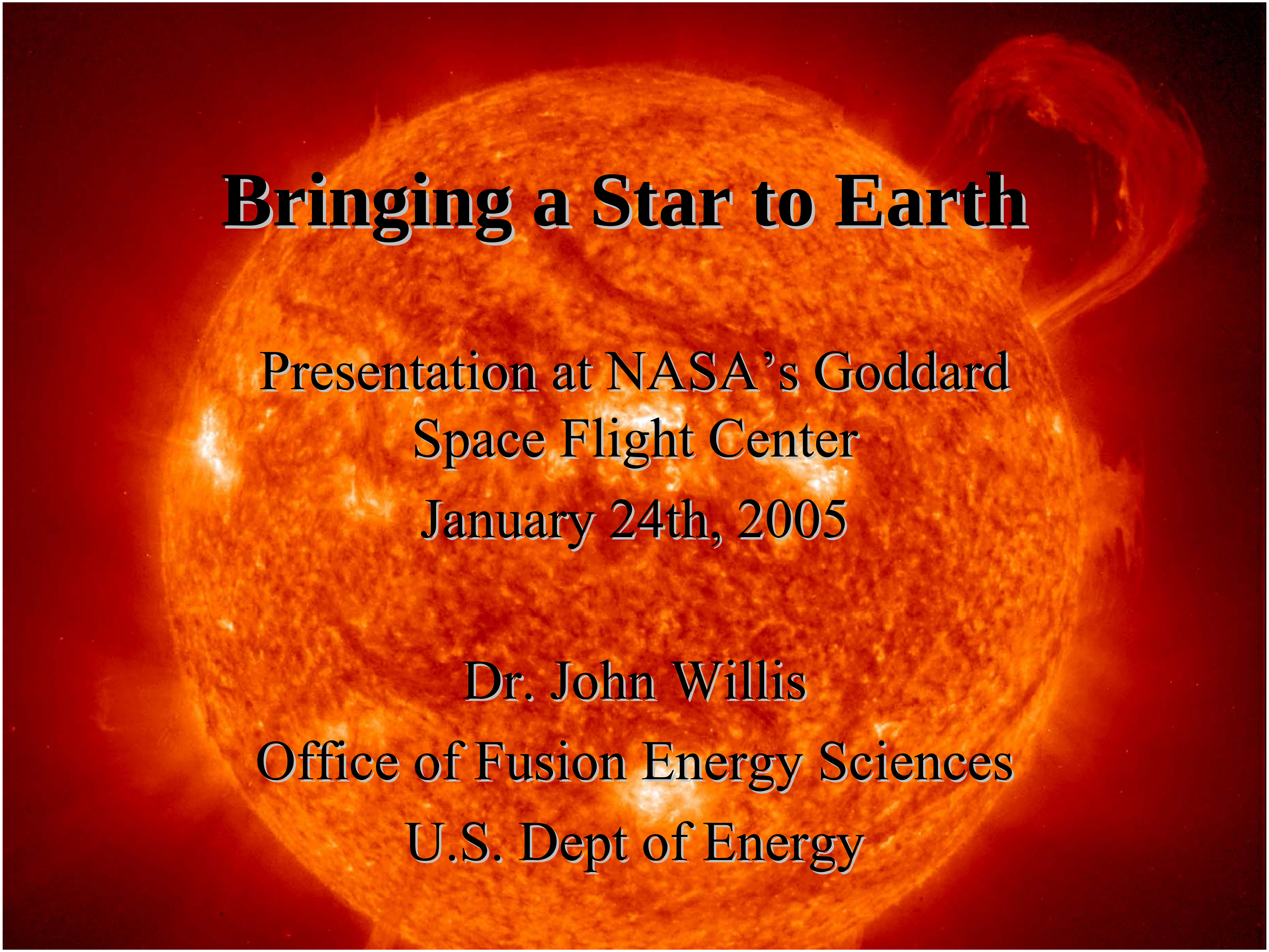


Bringing a Star to Earth

Presentation at NASA's Goddard Space Flight Center

January 24th, 2005

Dr. John Willis

Office of Fusion Energy Sciences

U.S. Dept of Energy

Topics

- Some Background
- The Current Program
- ITER
- And Beyond…

The Fusion Program and the Space Program have shared some common visionaries

"The road to useful power from fusion may be a long one, but the commanding importance of the goal continues to arouse strong commitments" — Lyman Spitzer

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

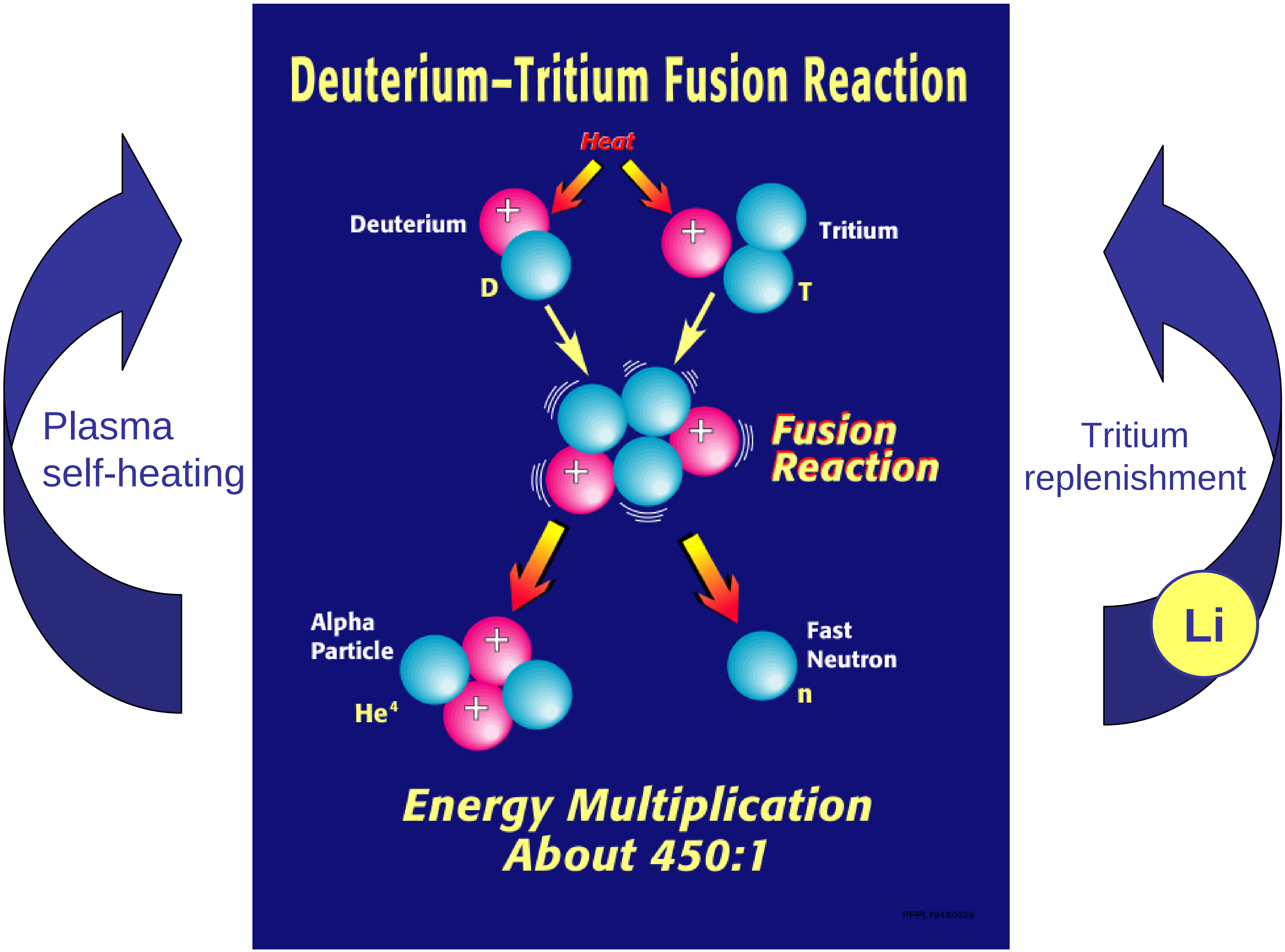
"Every time you look up at the sky, every one of those points of light is a reminder that fusion power is extractable from hydrogen and other light elements, and it is an everyday reality throughout the Milky Way Galaxy." --- Carl Sagan, Spitzer Lecture, October 1991

Galaxy M100 in the Virgo Cluster
From the Hubble Space Telescope

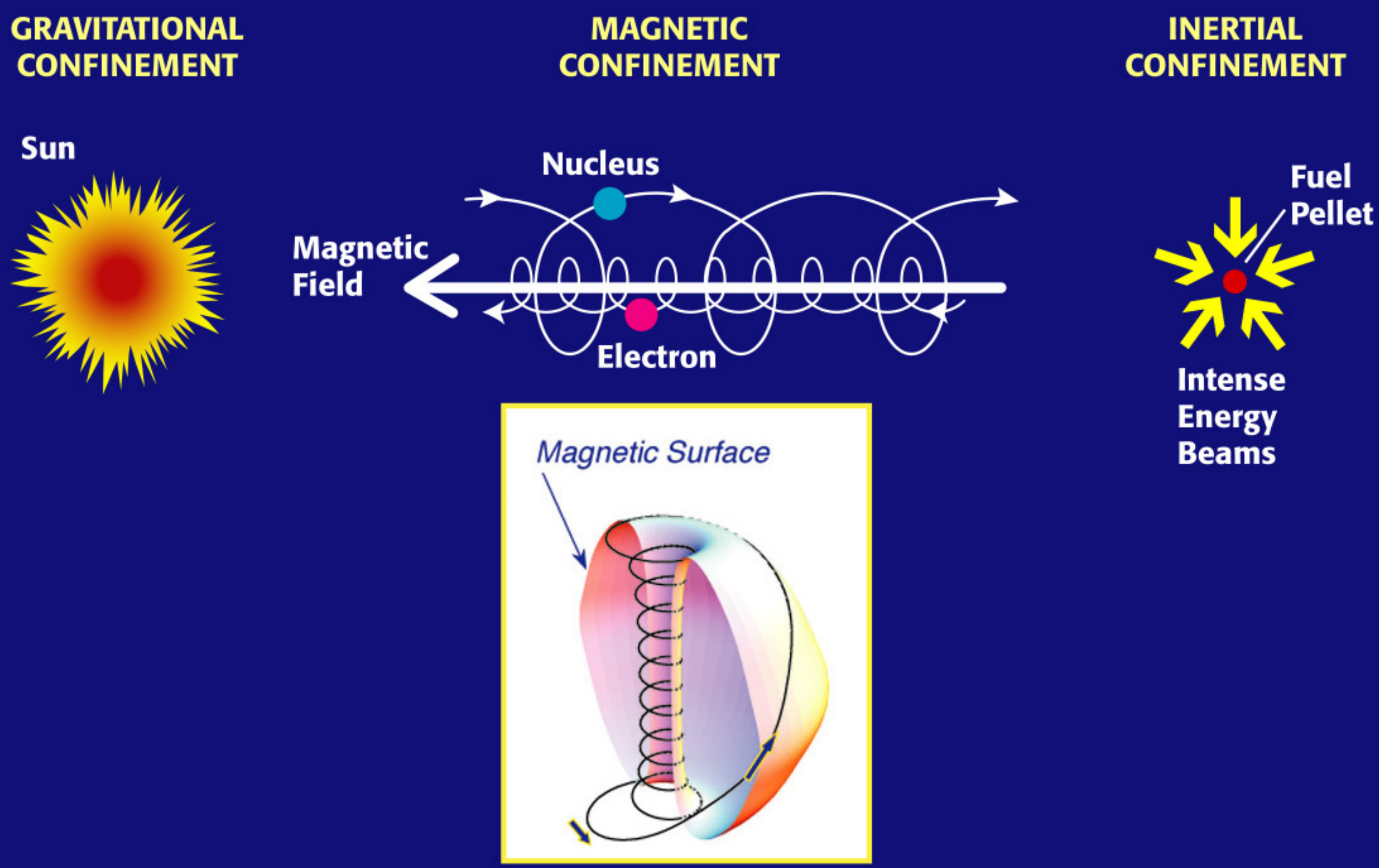
U.S. Fusion Energy Sciences Program Mission

"Advance plasma science, fusion science, and fusion technology-- the knowledge base needed for an economically and environmentally attractive fusion energy source."

- Community scientists have suggested this translates to the following goals:
  - Understand the dynamics of matter and fields in the high temperature plasma state.
  - Create and understand a controlled, self-heated, burning starfire on earth.
  - Make fusion power practical.


Deuterium–Tritium Fusion Reaction
Heat
Deuterium
D
Tritium
T
Fusion Reaction
Alpha Particle
He⁴
Fast Neutron
n
Energy Multiplication
About 450:1
Plasma self-heating
Tritium replenishment
Li

Plasma Confinement

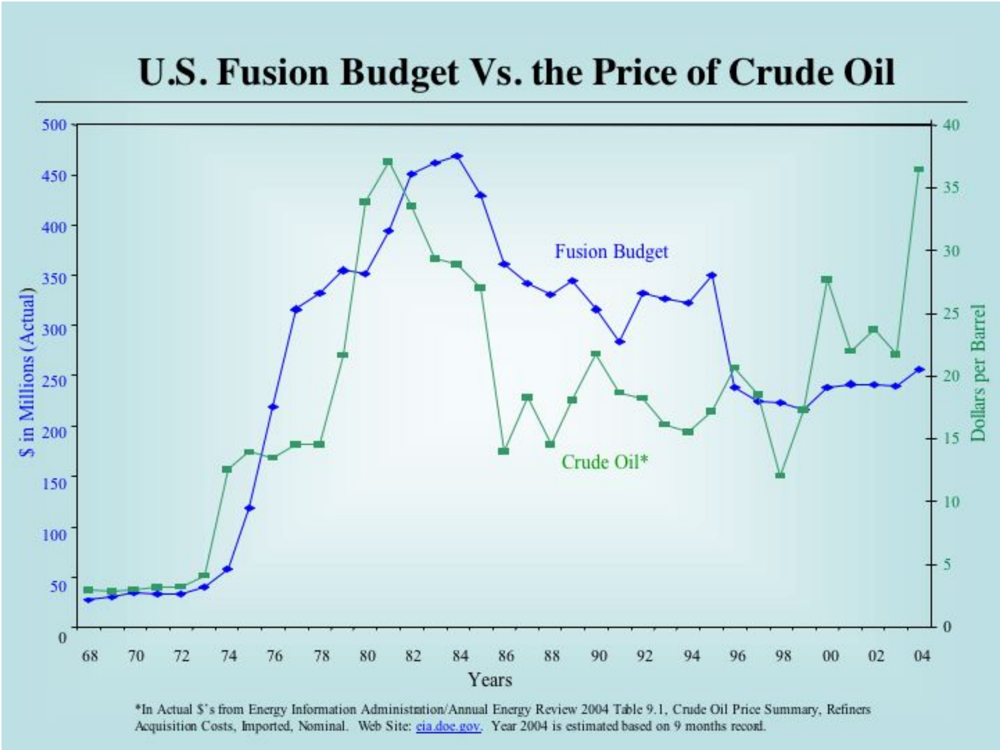


Fusion is a Potentially Attractive Domestic Energy Source

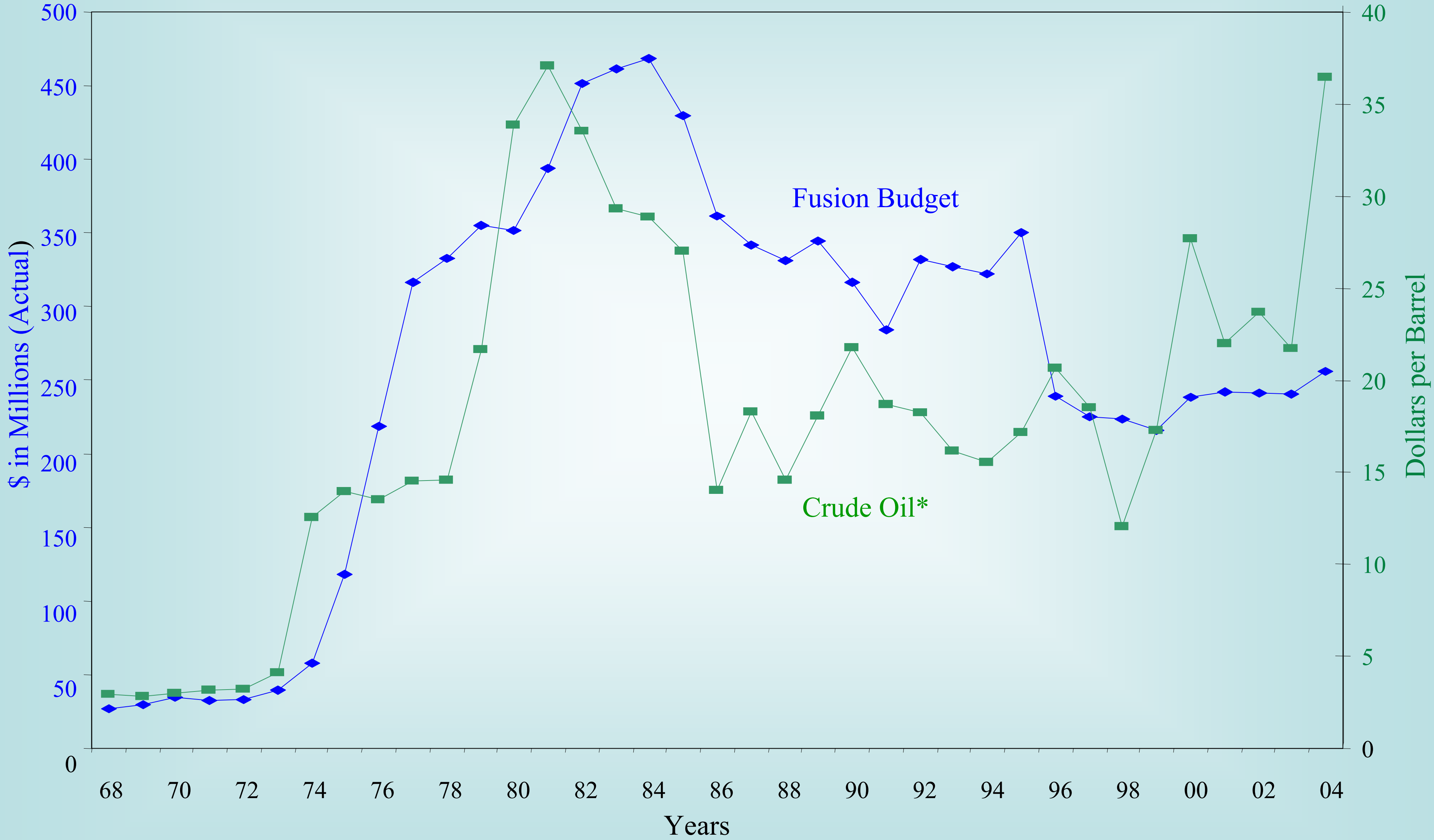
- Abundant fuel, available to all nations
  - Deuterium and lithium easily available for thousands of years
- Environmental Advantages
  - No carbon emissions, short-lived radioactivity
- Can't blow up, resistant to terrorist attack
  - Less than 5 minutes of fuel in the chamber
- Low risk of nuclear materials proliferation
  - No fissile or fertile materials required
- Compact relative to solar, wind and biomass
  - Modest land usage
- Not subject to daily, seasonal or regional weather variation
  - No large-scale energy storage nor long-distance transmission
- Cost of power estimated similar to coal, fission
- Can produce electricity and hydrogen
  - Complements other nearer-term energy sources

The U.S. Fusion Energy Sciences Program is Unique

- Science foundation/ Energy Mission
- Performers are diverse — Laboratory, University, & Industry
- International Partnerships
- Leveraged Connection to NNSA Programs in Inertial Fusion
- Funding level linked historically to price of oil

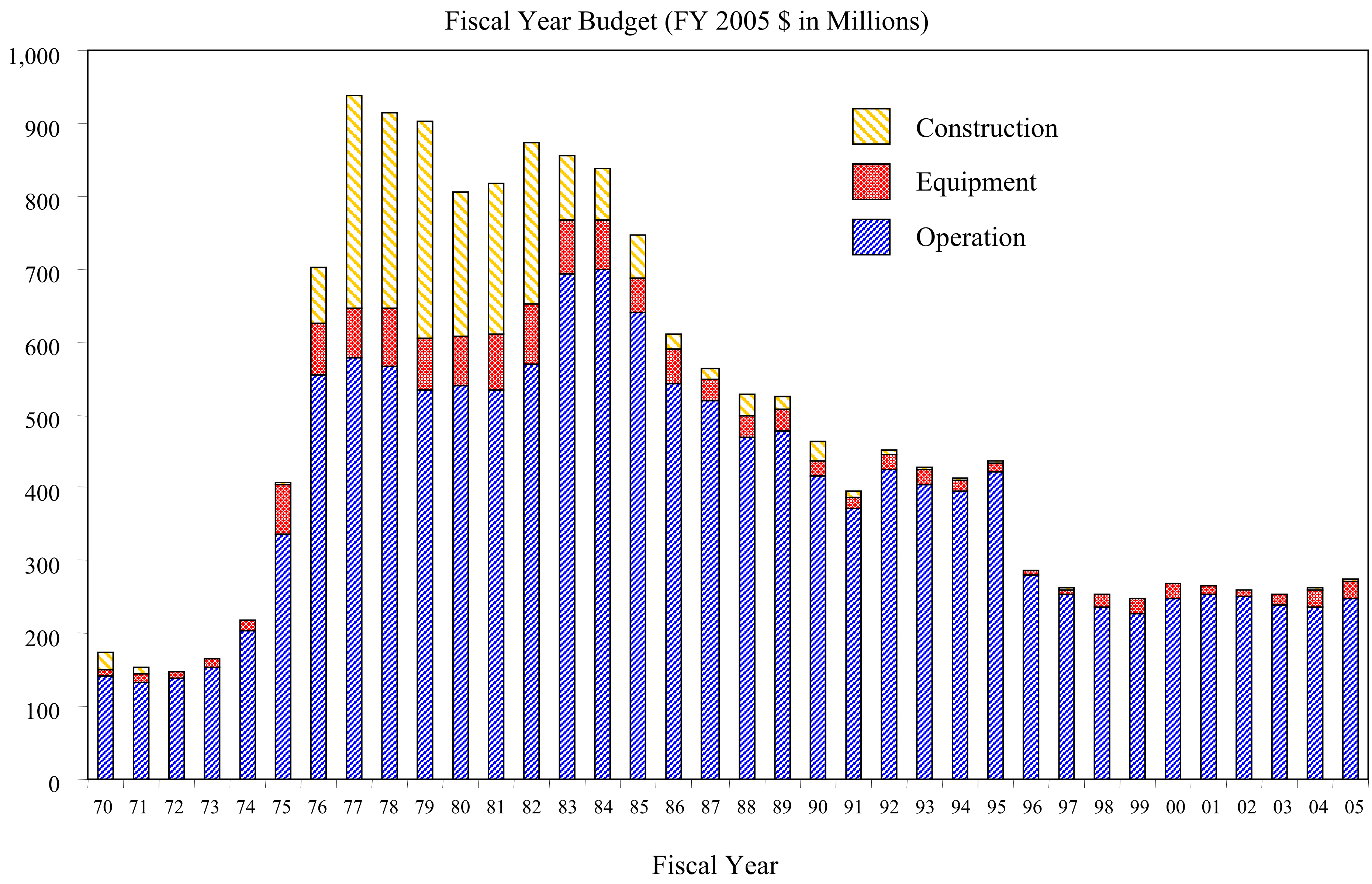


U.S. Fusion Budget Vs. the Price of Crude Oil

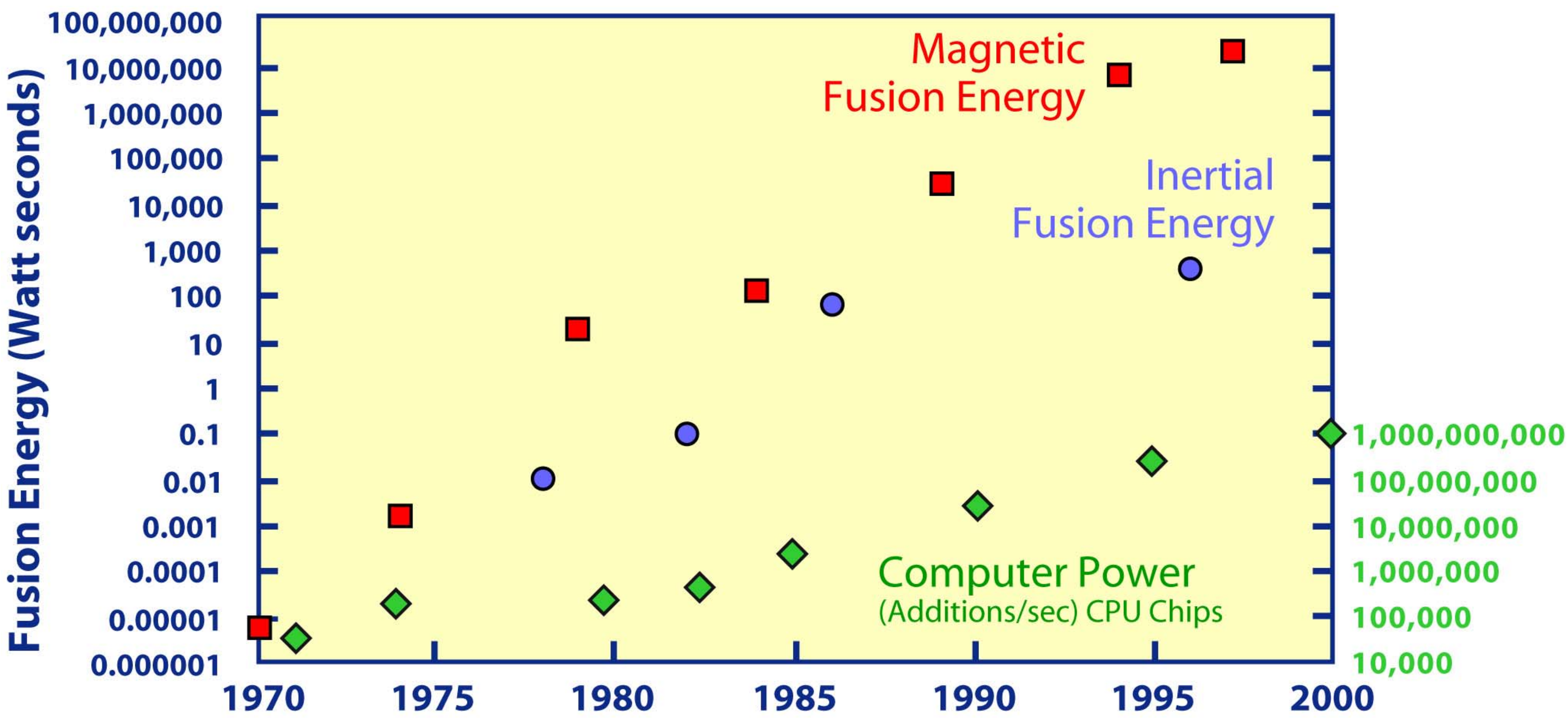


*In Actual $'s from Energy Information Administration/Annual Energy Review 2004 Table 9.1, Crude Oil Price Summary, Refiners Acquisition Costs, Imported, Nominal. Web Site: eia.doe.gov. Year 2004 is estimated based on 9 months record.

U.S. Fusion Energy Sciences Budget History

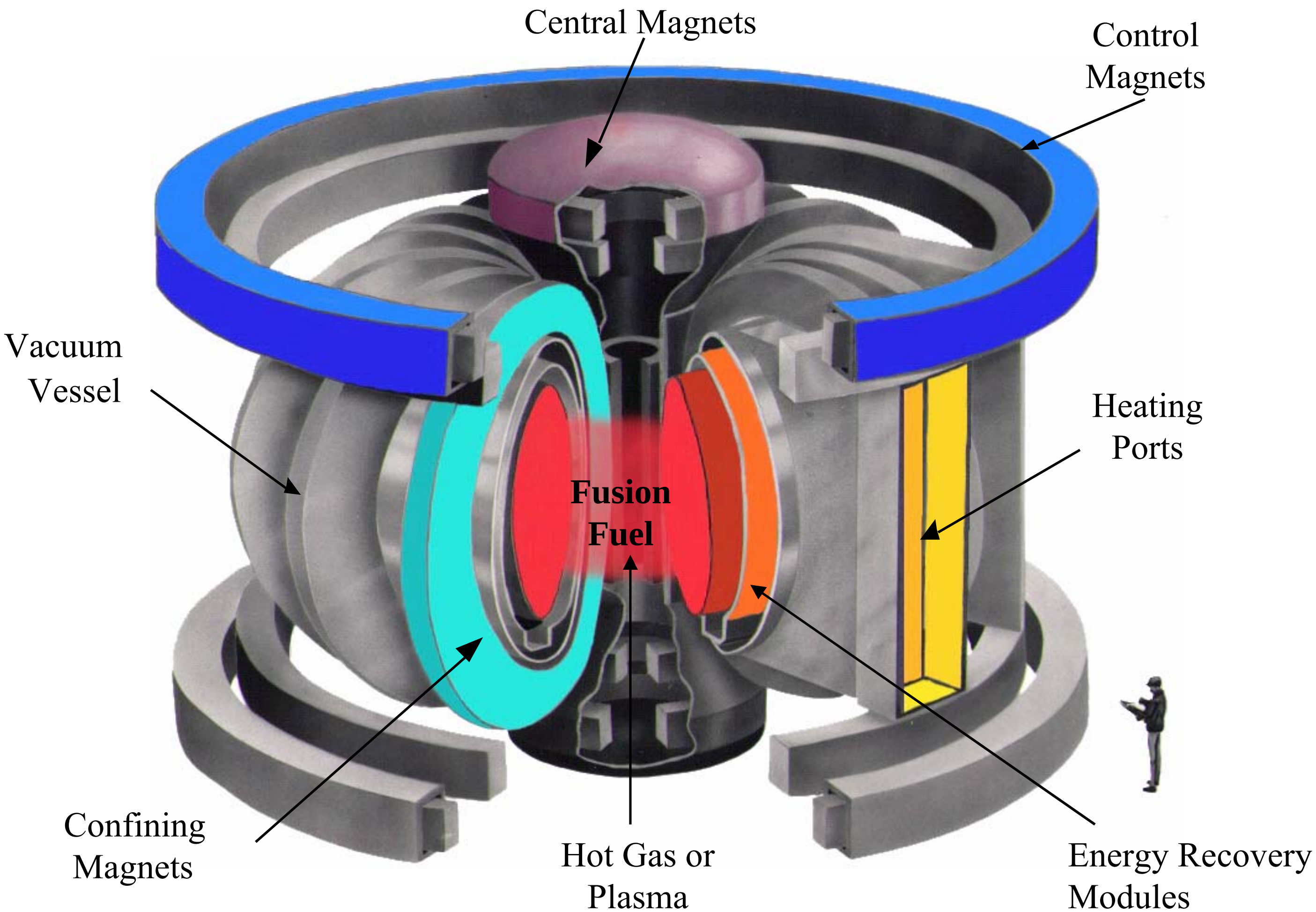


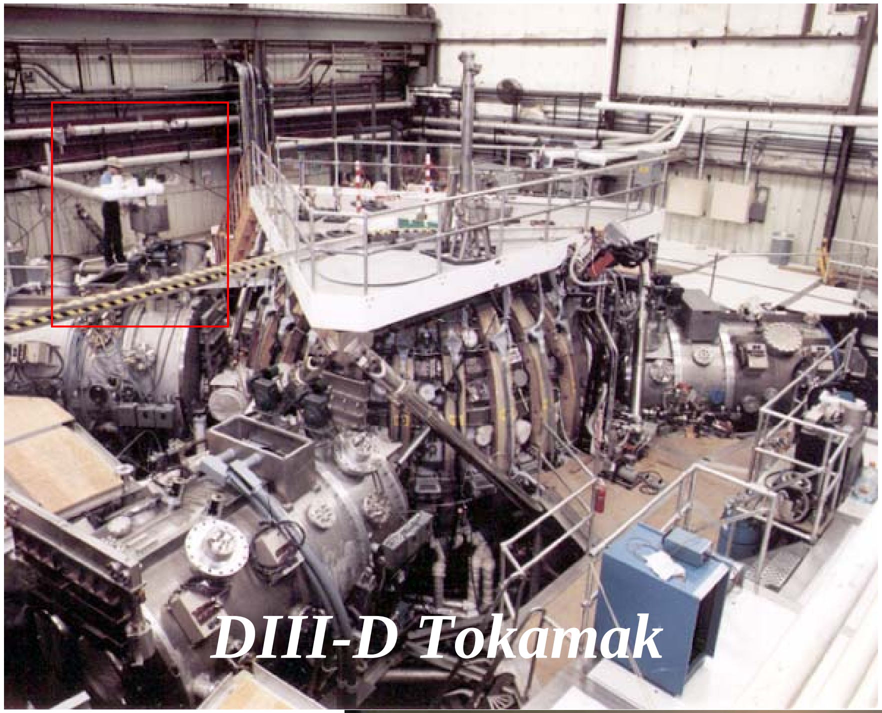
Progress in Fusion has Outpaced Computer Speed



Progress is paced by the construction of new facilities.

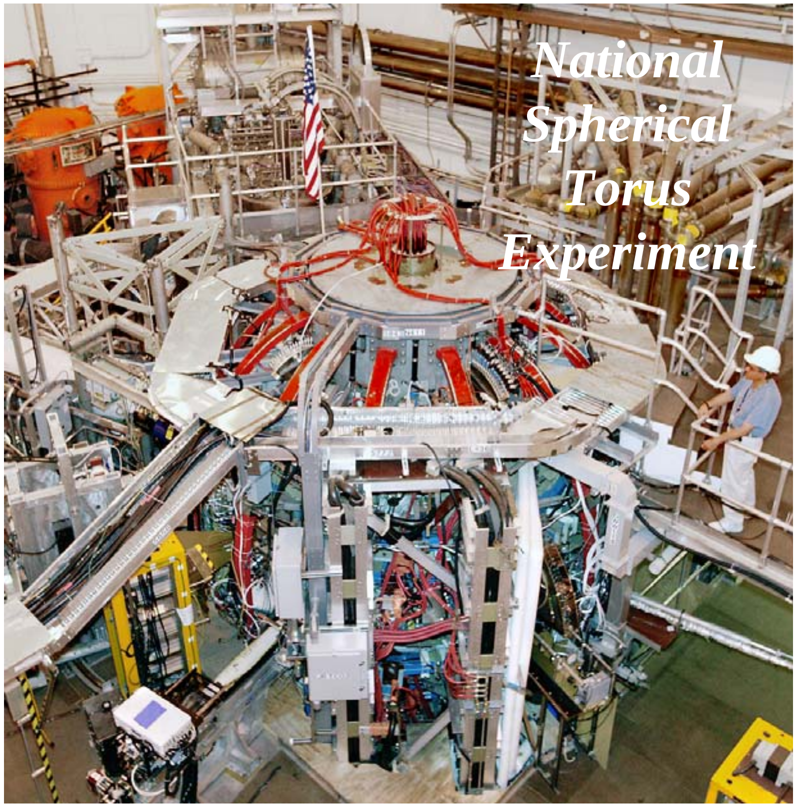
Most Developed Fusion Concept is the Tokamak





General Atomics

Doublet III Started Operations In 1978



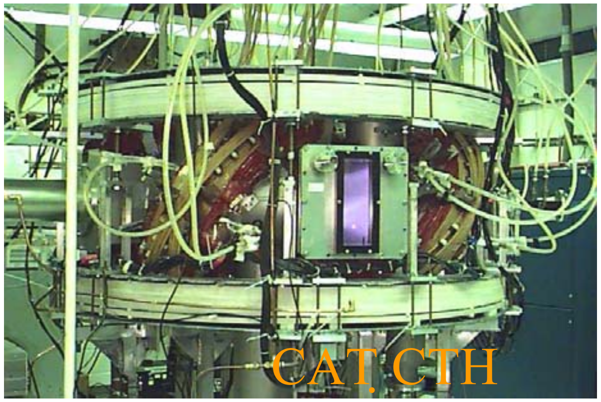
Princeton Plasma Physics Laboratory

NSTX started Operations in 1999

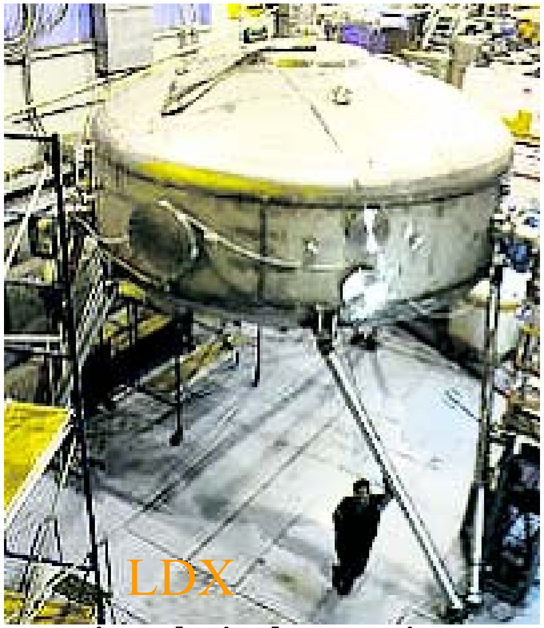
Massachusetts Institute of Technology

C-MOD Started Operations in October 1991

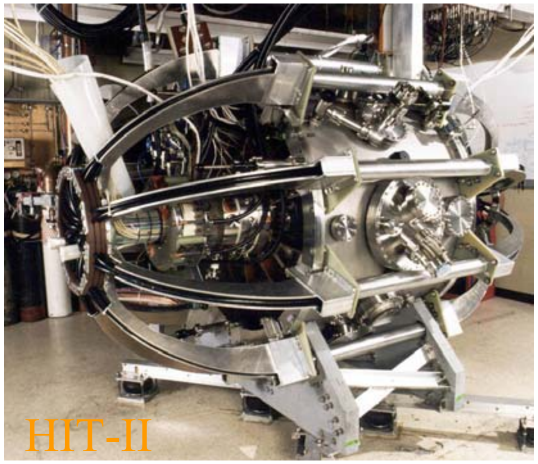
Innovative Confinement Concepts being tested at smaller scale



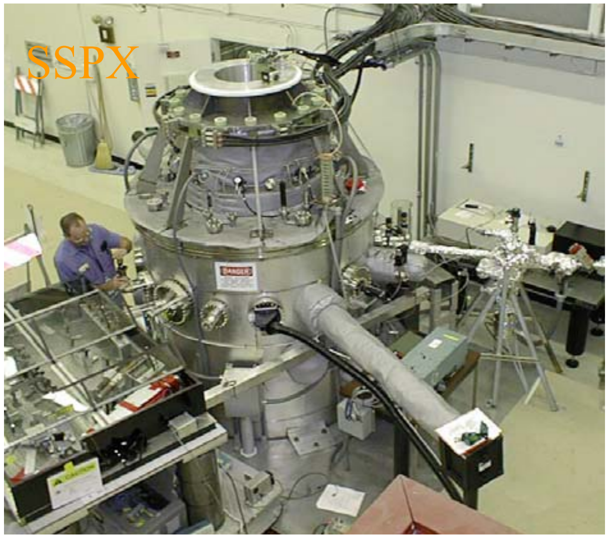
Compact Auburn Torsatron becoming
Compact Toroidal Hybrid
Auburn University, Auburn Alabama



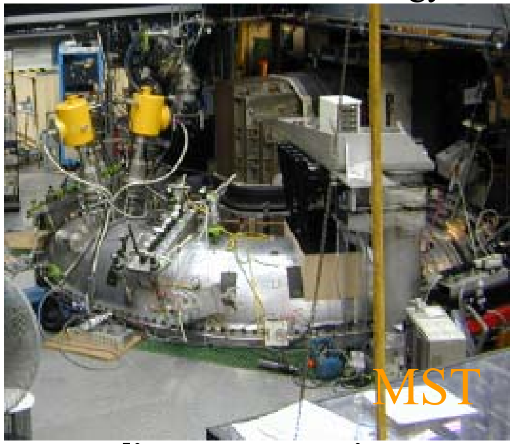
Levitated Dipole Experiment
Columbia University/Massachusetts Institute of Technology



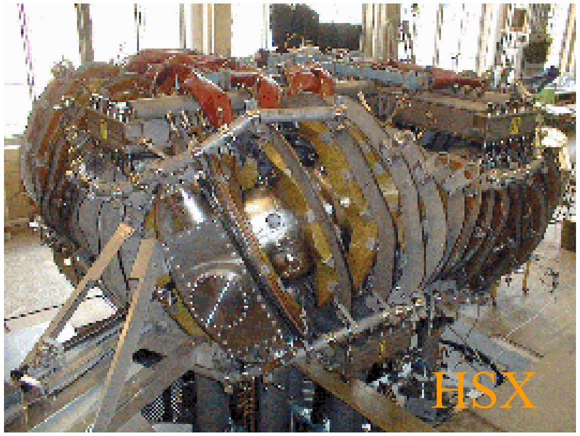
Helicity Injected Torus-II Experiment
University of Washington, Seattle



Sustained Spheromak Plasma Experiment
Lawrence Livermore National Laboratory

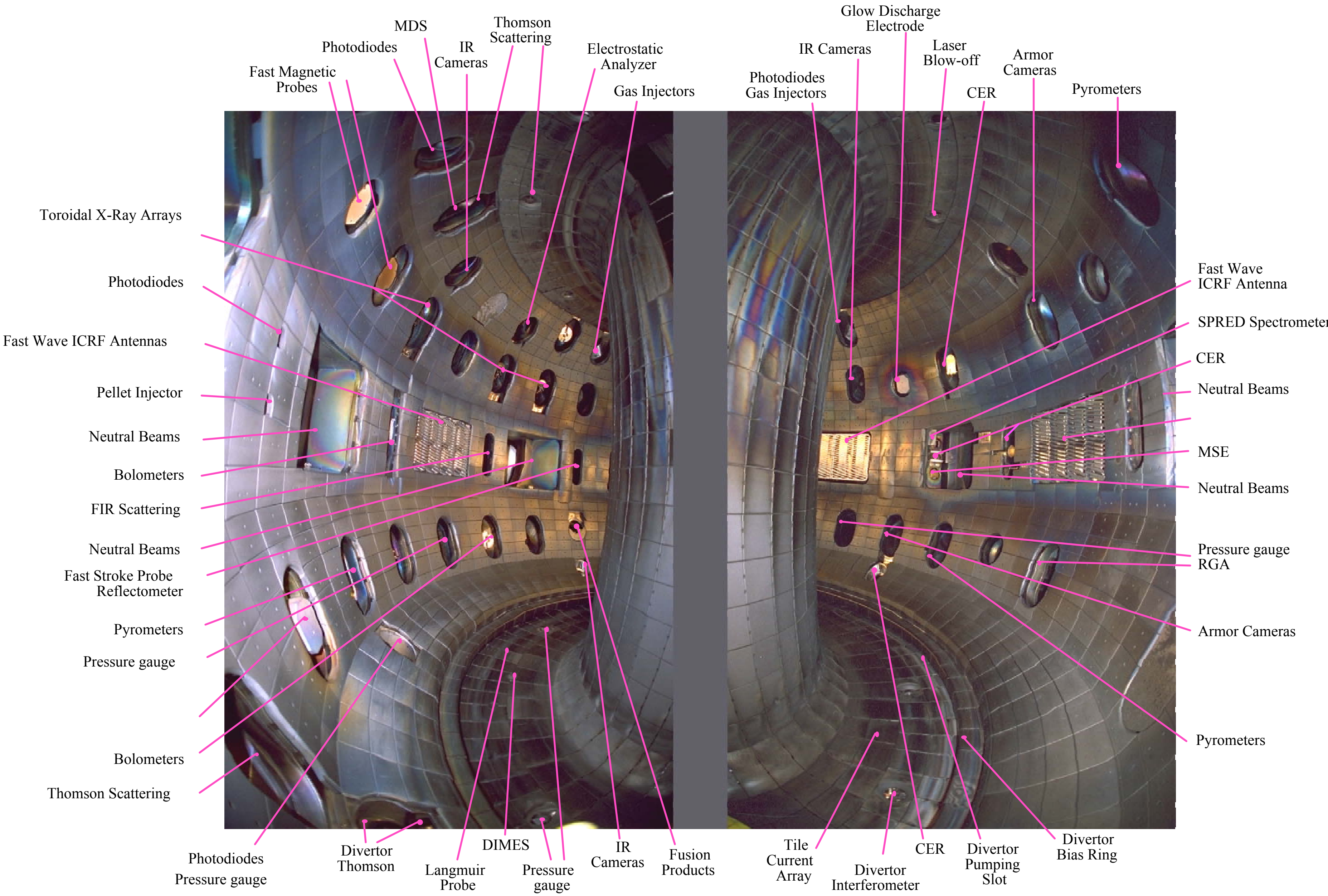


Madison Symmetric Torus
University of Wisconsin, Madison



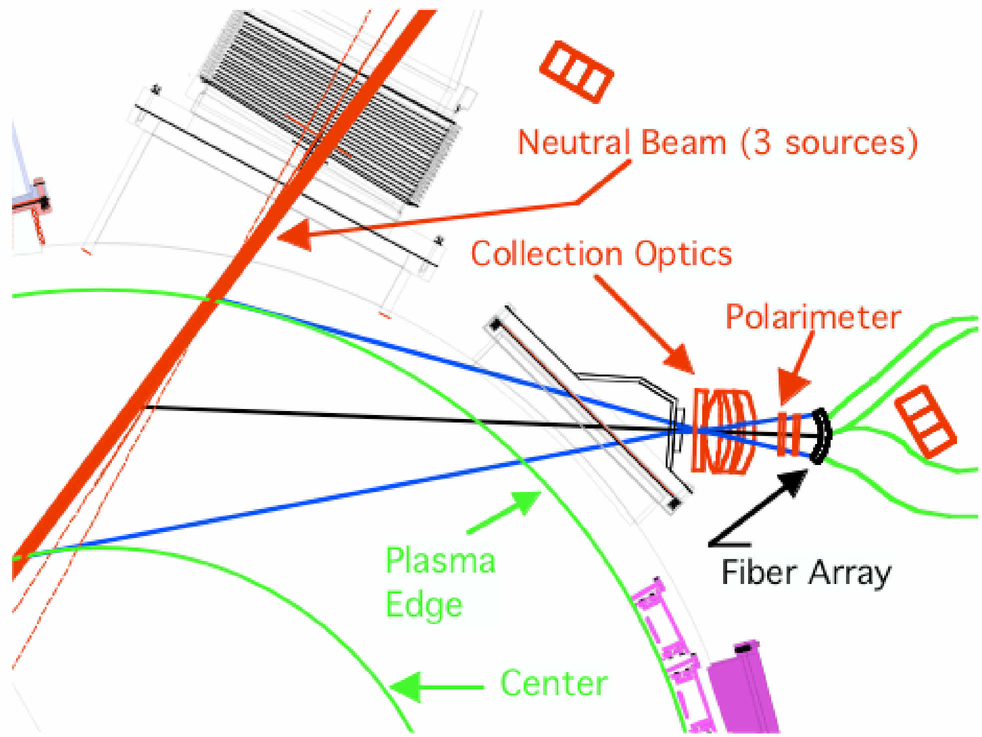
Helically Symmetric Experiment
University of Wisconsin, Madison

Existing DIID–D Diagnostic Set is Extensive

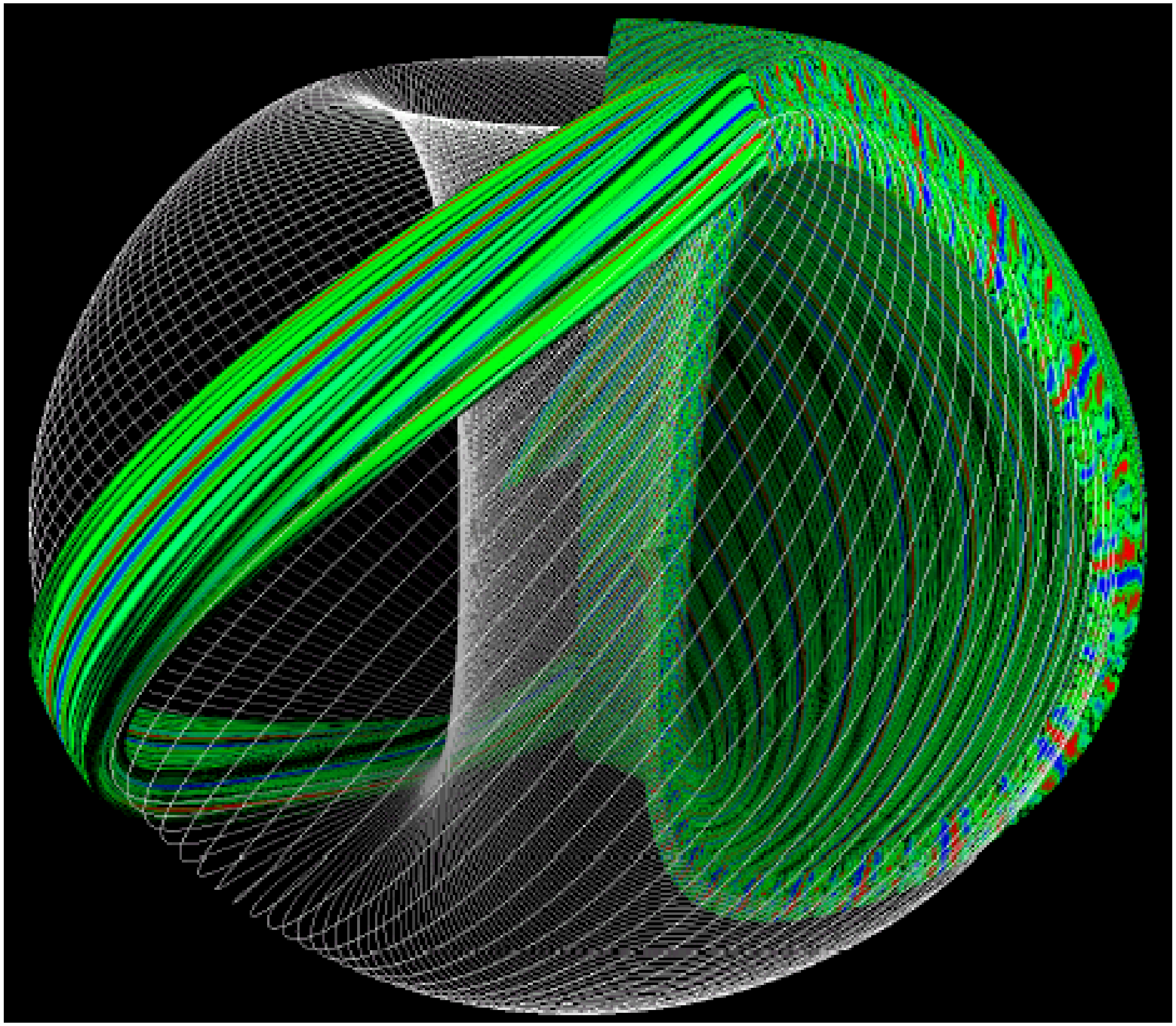


Motional Stark Effect Measurements of Field Angle has Revolutionized Stability Studies

- Motional Stark Effect depends on v x B $\Rightarrow$ E.
  - Linear effect in D_0 beam injected into plasma, crossing magnetic field.
- Allows highly localized measurement of B field tilt, to a fraction of a degree.
- Revolutionized stability studies by allowing detailed measurements of internal magnetic fields.
  - Typical confidence level in pressure limits ~ 15%

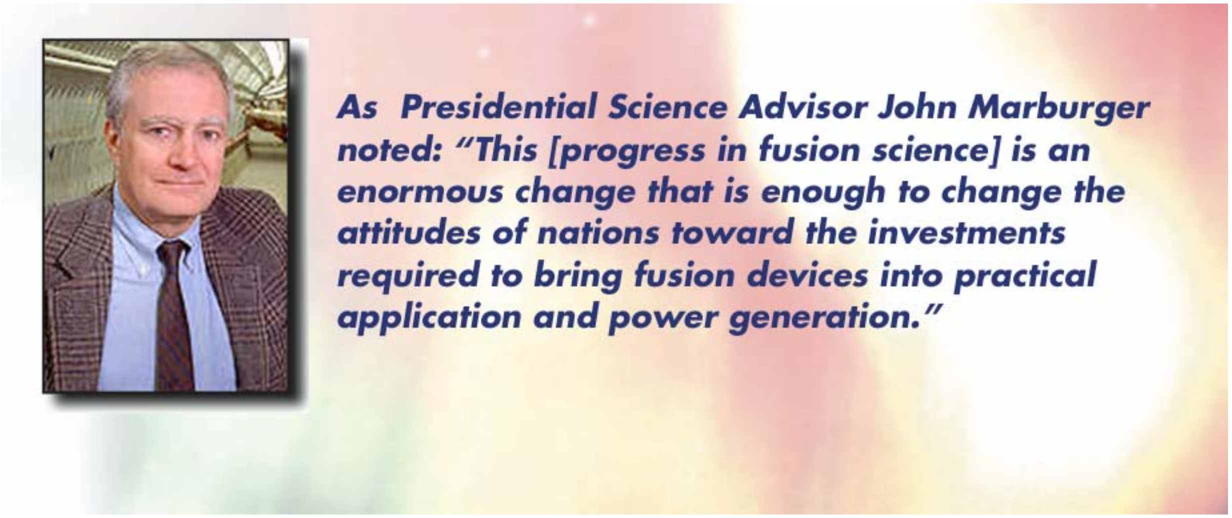


Advanced Scientific Computing in Fusion Energy Sciences



Fusion Research has changed dramatically over the last decade

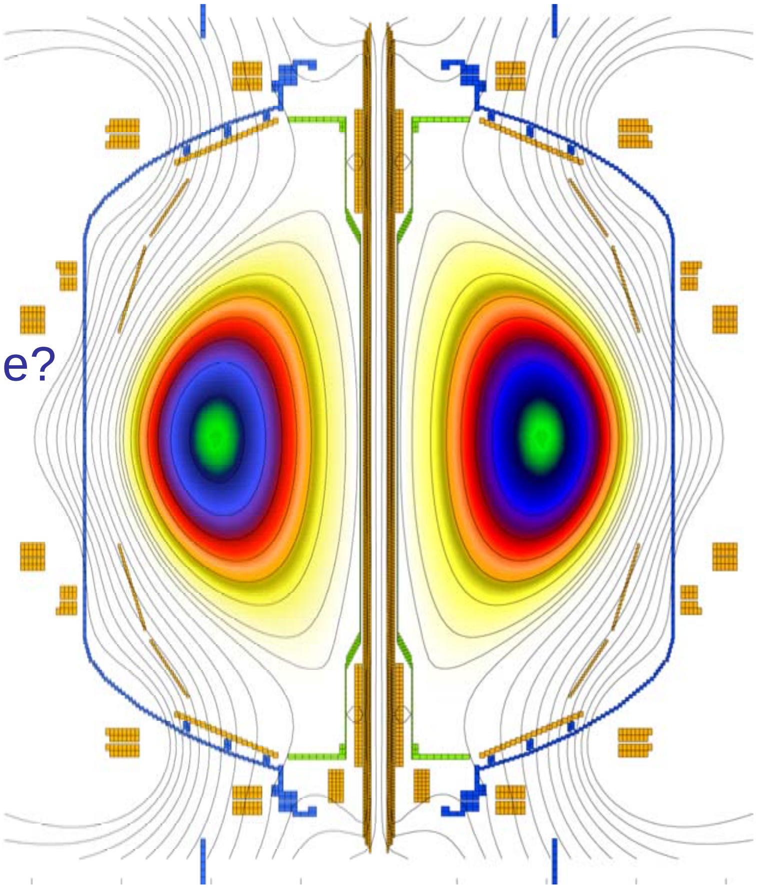
- Increasingly detailed measurements, deeper theoretical understanding, and large-scale computational tools enable modeling of real configurations.
- The basic mechanisms have been identified, and the earlier empirical predictions have been put on more solid ground.
- Today, we can reliably create, measure, model, and predict experimental plasma behavior to such a degree that large-scale energy production can be designed with much improved confidence.



Fusion Plasma Science Challenges

NAS Plasma Science Committee

- Global Stability
  - What limits the pressure in plasmas?
    - Solar flares
- Wave-particle Interactions
  - How do hot particles and plasma waves interact in the nonlinear regime?
    - Magnetospheric heating
- Microturbulence & Transport
  - What causes plasma transport?
    - Accretion disks
- Plasma-material Interactions
  - How can high-temperature plasma and material surfaces co-exist?
    - Micro-electronics processing



Basic Scaling of Turbulent Transport Depends on Eddy Size

- David Bohm proposed a worst-case thermal diffusion model for plasmas, where eddies are system-scale:

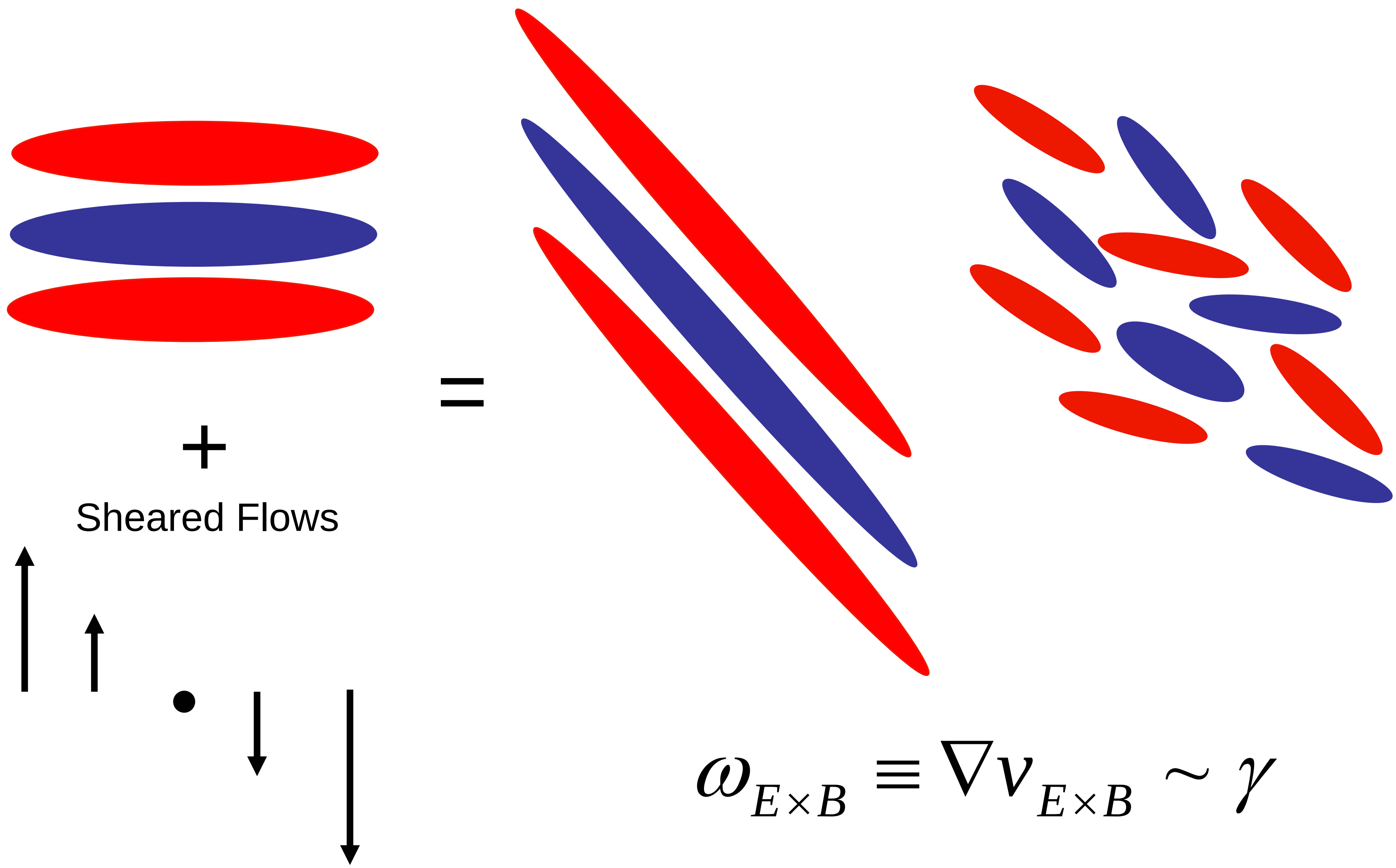
- The standard "gyro-Bohm" model of strong ion-scale drift-wave turbulence assumes eddies scale as ρ_i

Sheared Flows can Reduce or Suppress Turbulence

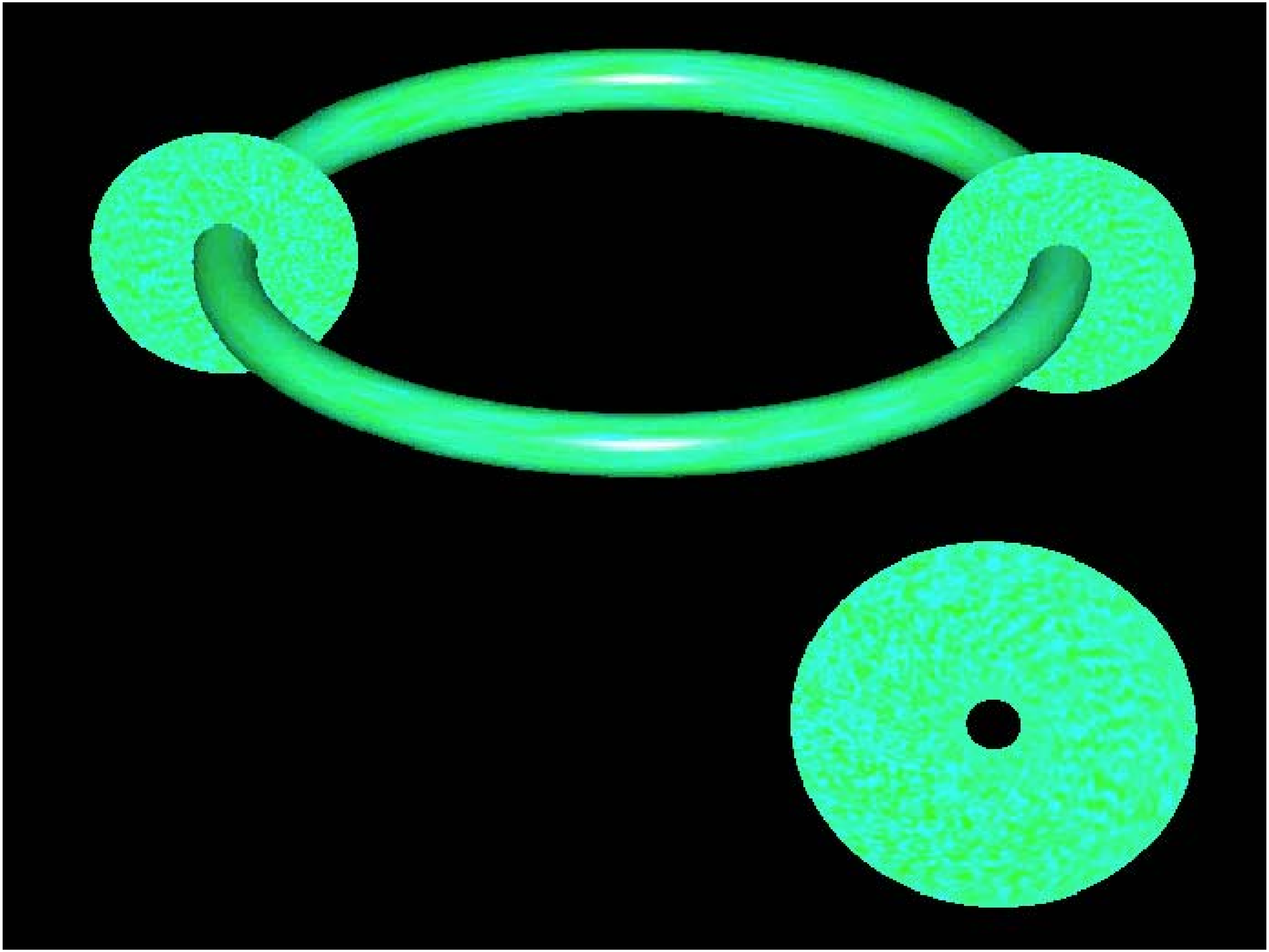
Most Dangerous Eddies:
Transport long distances

Sheared Eddies
Less effective

Eventually break up



$$\omega_{E\times B} \equiv \nabla v_{E\times B} \sim \gamma$$



Direct Measurements of Turbulence Supports Gyro-Bohm + Shear Stabilization Model

- Movies of turbulent fluctuations in plasma density via beam emission spectroscopy – excitation radiation from beam neutral collisions with plasma ions and electrons.

(Frame rate: 1,000,000 /sec)

- Confirms ~ predicted $\delta n/n$ strongest at edge, and weaker in plasma core. Spectrum ~ theory

Height

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

Radius

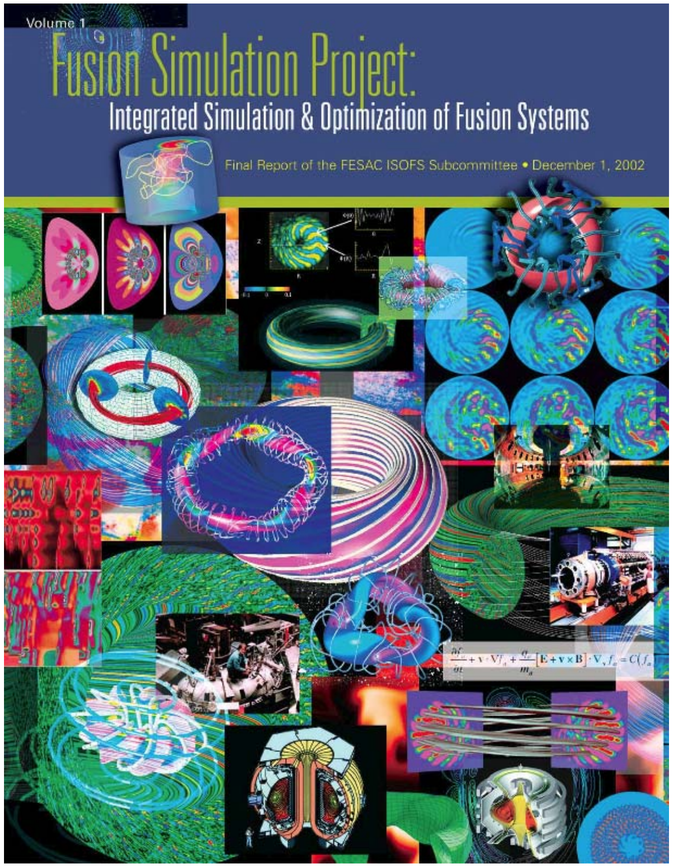
Fusion Simulation Project

- The Fusion Simulation Project (FSP) will unify and accelerate progress on a complete, integrated simulation and modeling capability for ITER-class burning plasma

- Creating this capability entails integrating physics that heretofore has largely been considered in isolation

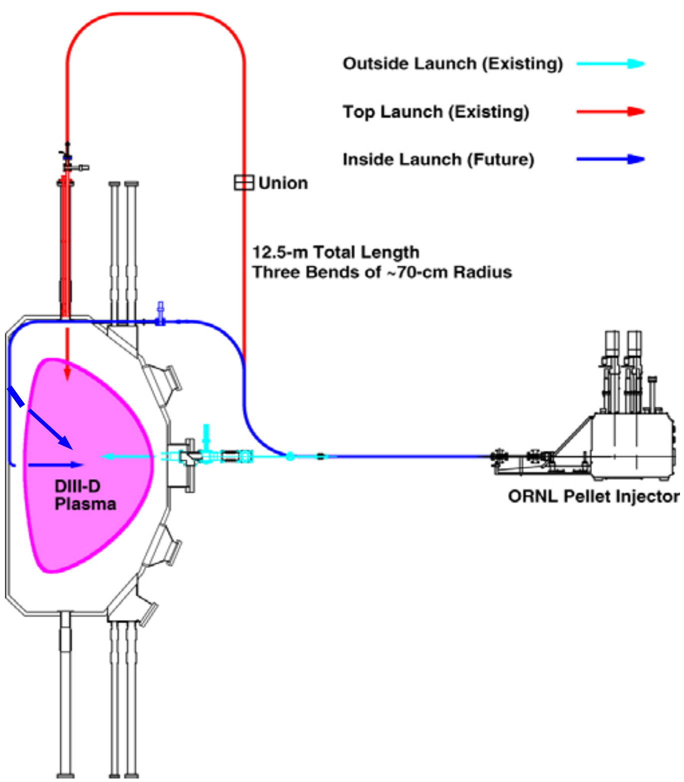
- The fusion environment poses particular difficult challenges in terms of the range of spatial and temporal scales that must be computed

- In FY 2005, we will begin the first phase of the FSP by soliciting proposals for the initial integration efforts called “Focused Integration Initiatives” in the FESAC Report



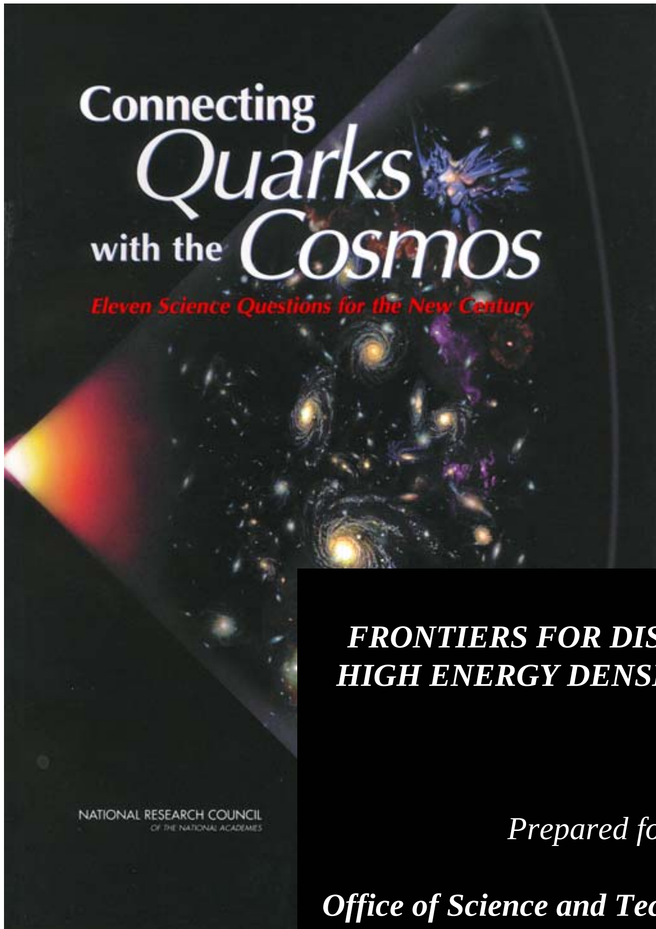
Enabling Technologies Program

Pellet Injector in DIII-D for Plasma Fueling



100 GHz Gyrotron Tube (1MW power in 1 second pulse) for Plasma Heating and Control

DiMES probe in DIII-D provides data on plasma material interactions.



FRONTIERS FOR DISCOVERY IN HIGH ENERGY DENSITY PHYSICS

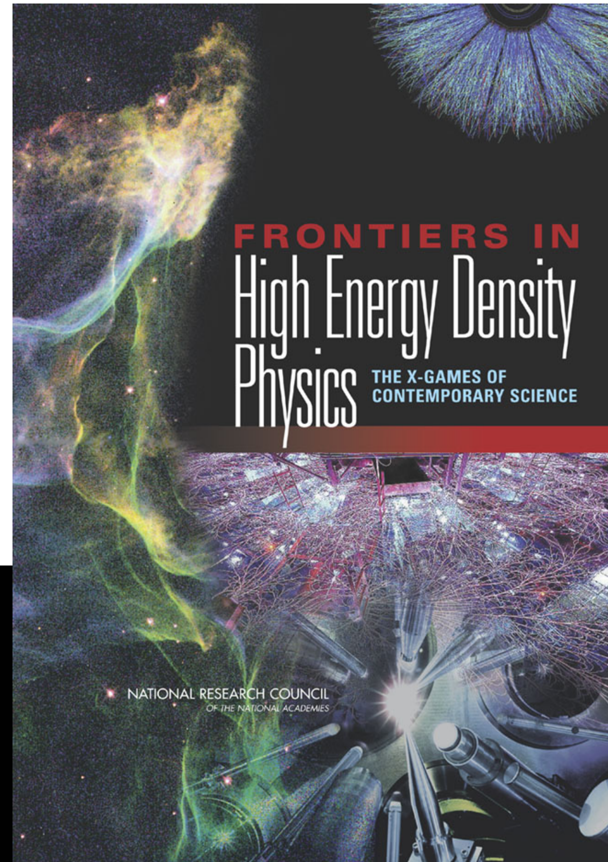
Prepared for

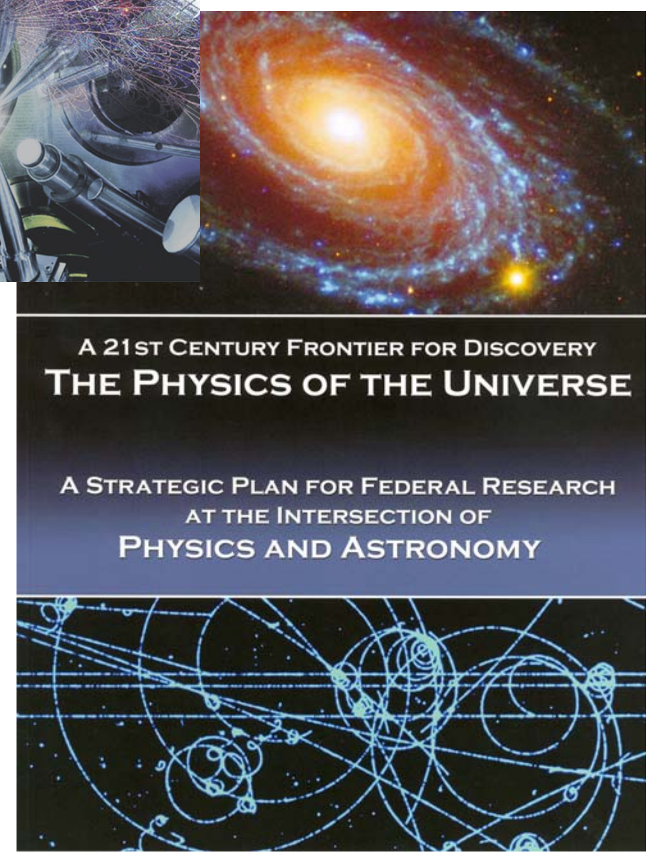
Office of Science and Technology Policy
National Science and Technology Council
Interagency Working Group on the Physics of the Universe

Prepared by

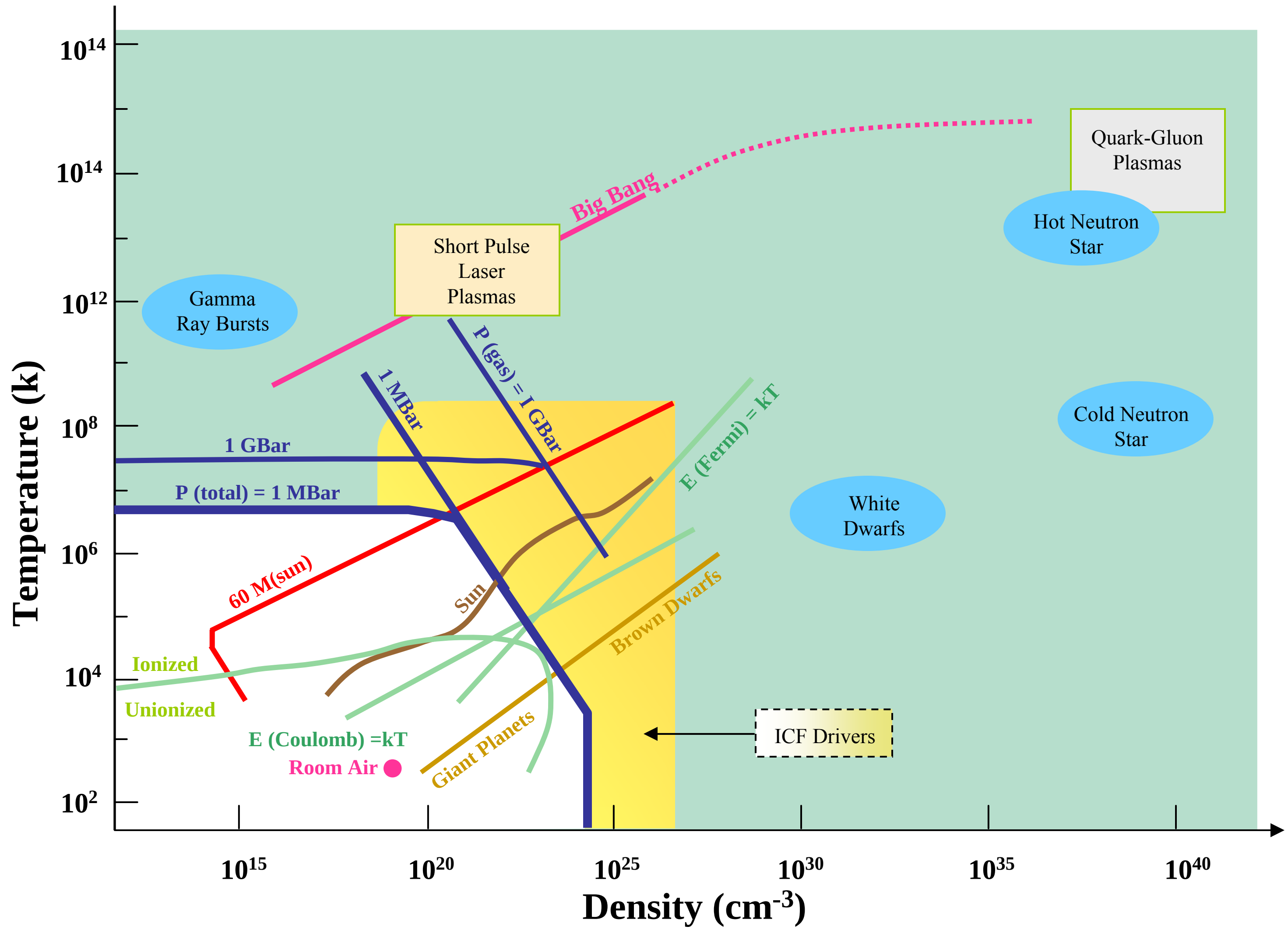
National Task Force on High Energy Density Physics

July 20, 2004

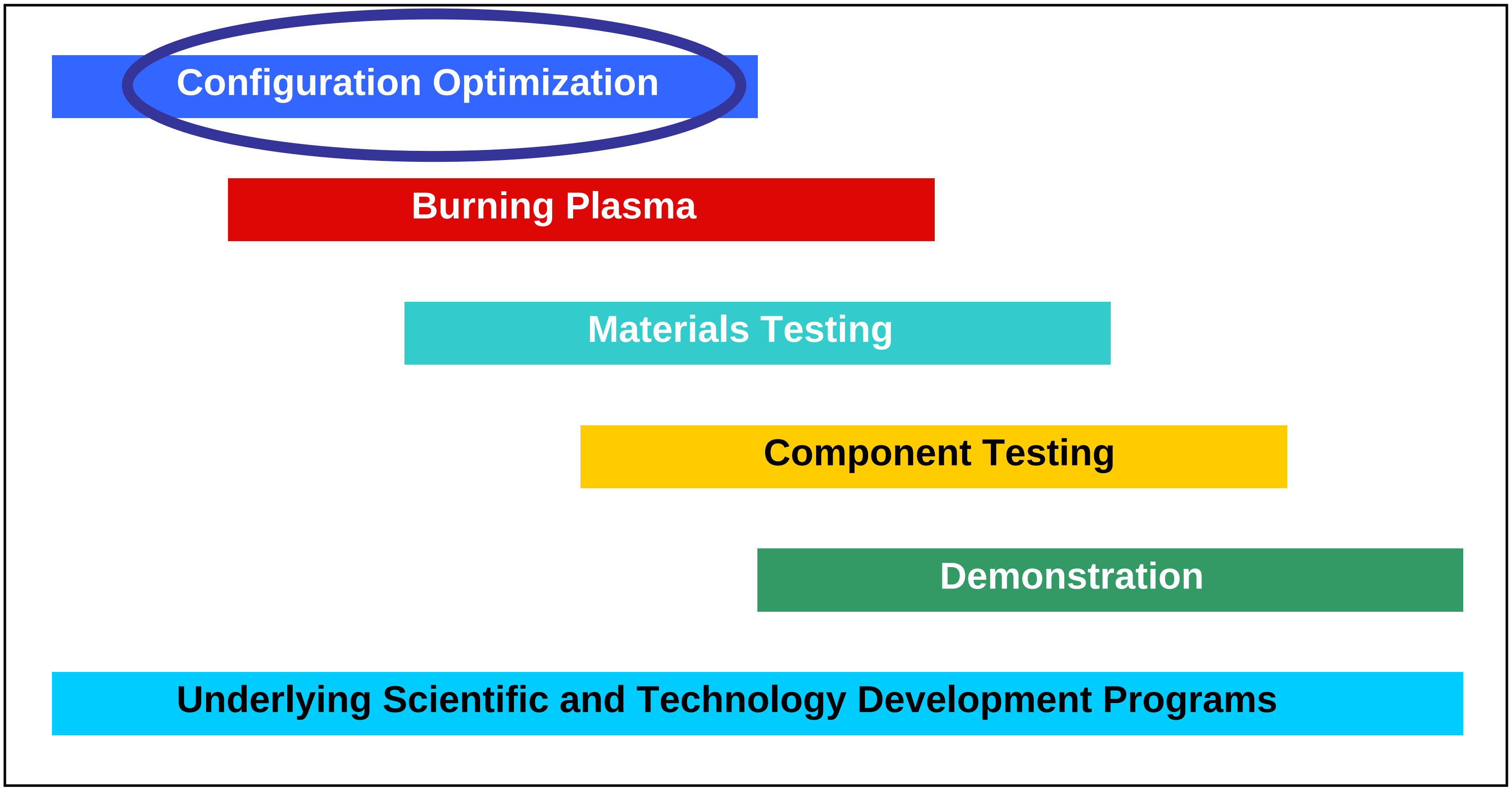




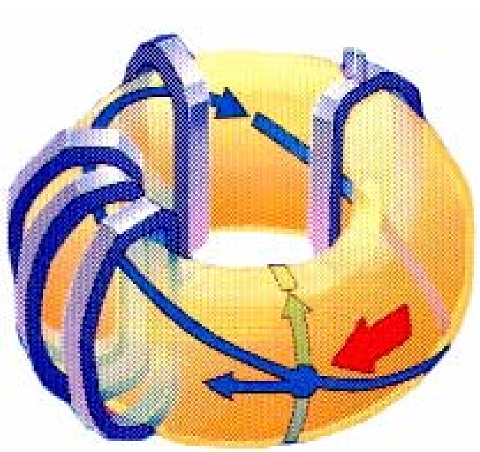
Map of the HED Universe



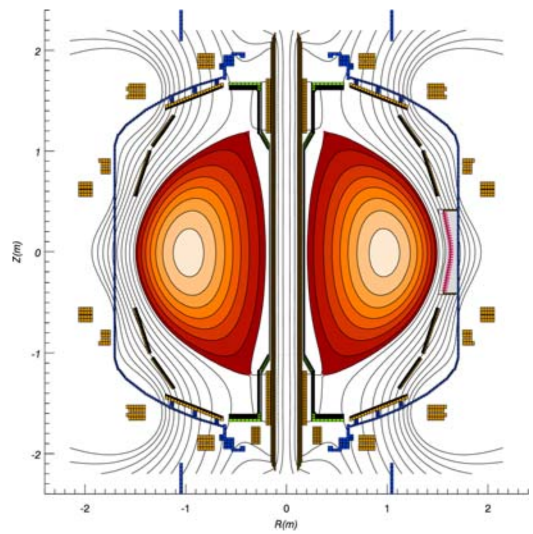
The Fusion Development Path is Defined by a Set of Overlapping Scientific and Technological Challenges



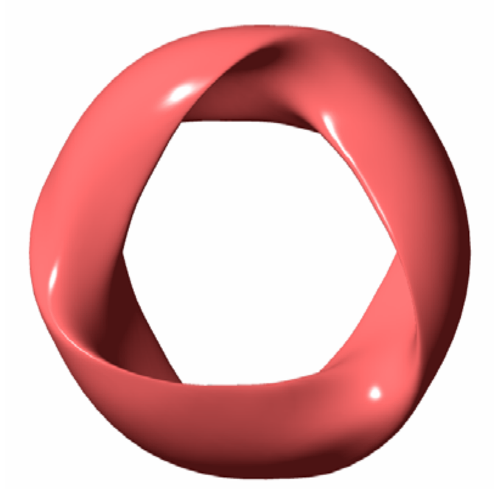
Configuration Optimization is a Key Step in Fusion Development



Advanced Tokamak
Active instability control and driven steady-state.



Spherical Torus
High plasma pressure at low magnetic field.



Compact Stellarator
Passive stability and steady-state operation.

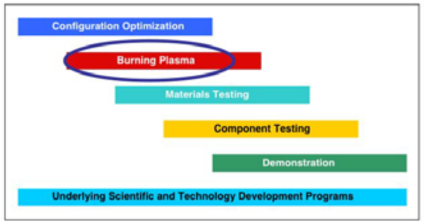
Joining Innovation with Results from ITER with the Goal of High Power Density and Continuous Operation

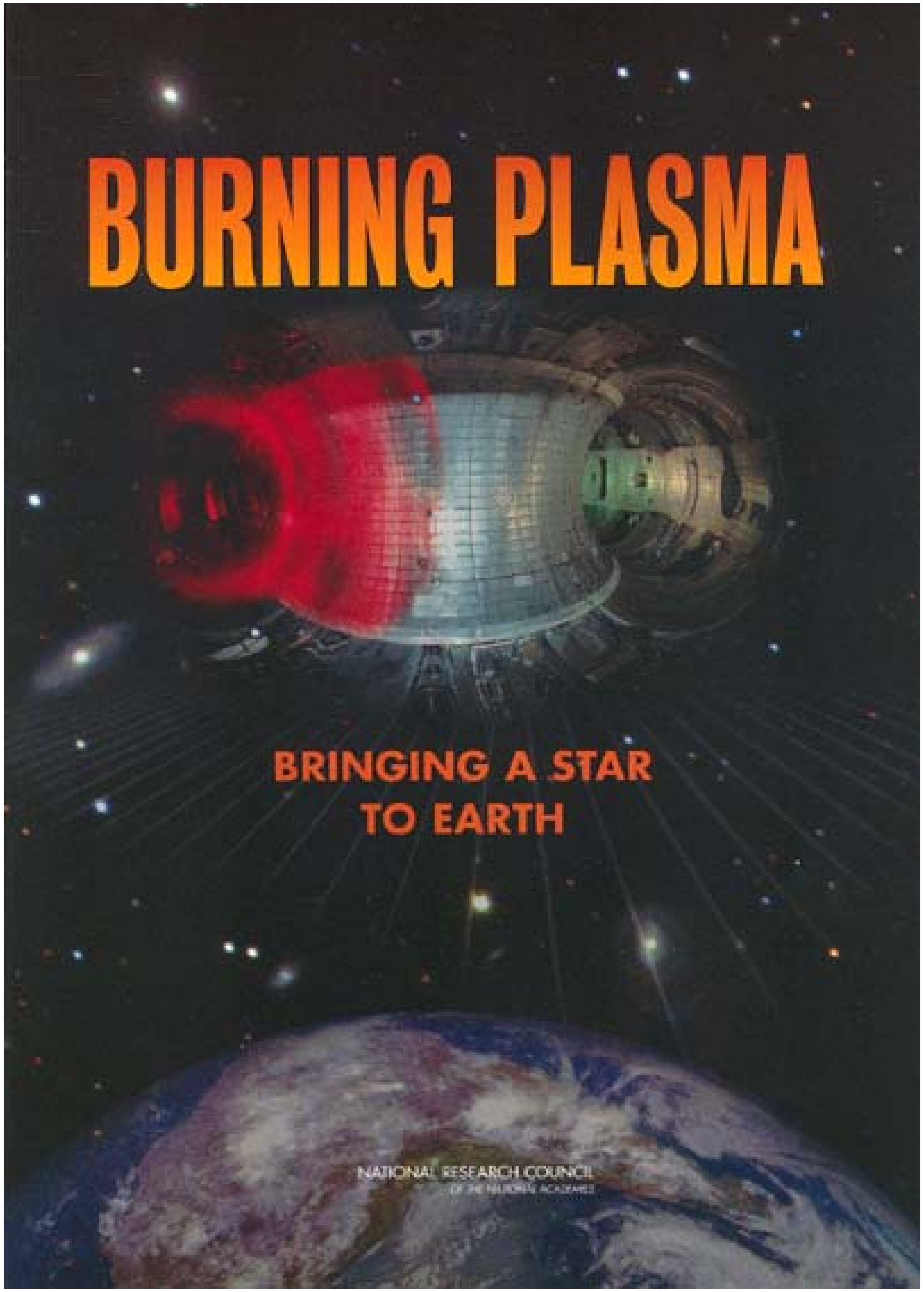
Report of the Burning Plasma Assessment Committee

Released September 2003

- o U.S. participation in ITER
- o Fusion program priority setting

The Fusion Development Path is Defined by a Set of Overlapping Scientific and Technological Challenges





Office of Science

20 Year Facilities Plan

"These Department of Energy facilities are used by more than 18,000 researchers from universities, other government agencies, private industry and foreign nations."

- Secretary of Energy
Spencer Abraham

From the

Office of Science

20 Year Facilities Plan

Facility Summaries

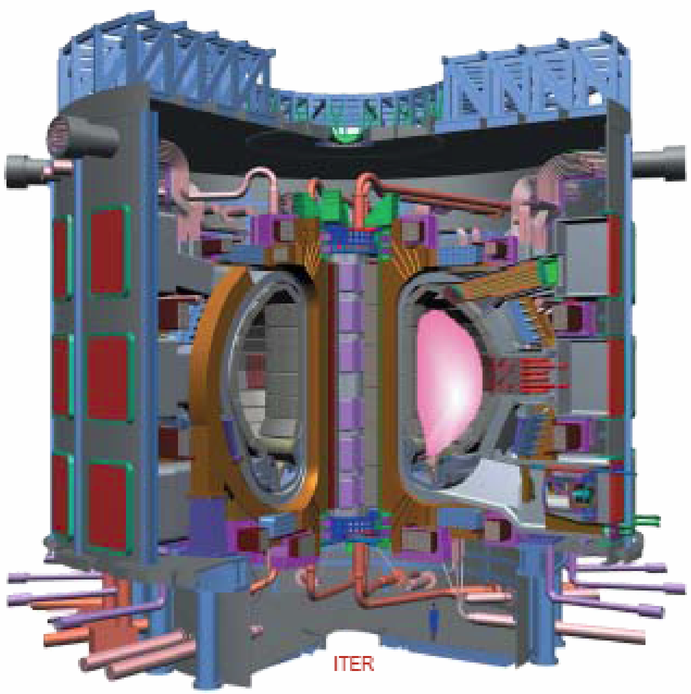
Near-Term Priorities

Priority: 1
ITER

The Facility: ITER is an international collaboration to build the first fusion science experiment capable of producing a self-sustaining fusion reaction, called a "burning plasma." It is the next essential and critical step on the path toward demonstrating the scientific and technological feasibility of fusion energy.

Background: Fusion is the power source of the sun and the stars. It occurs when the lightest atom, hydrogen, is heated to very high temperatures forming a special gas called "plasma." In this plasma, hydrogen atoms combine, or "fuse," to form a heavier atom, helium. In the process of fusing, some matter is converted directly into large amounts of energy. The ability to contain this reaction, and harness the energy from it, are among the important goals of fusion research.

What's New: Recent advances in computer modeling and in our understanding of the physics of fusion give us confidence that we can now build ITER successfully. The unique features of the facility will be its ability to operate for long durations (hundreds of seconds and possibly several thousands) and at power levels (around 500 MW) sufficient to demonstrate the physics of the burning plasma in a power-plant-like environment. ITER will also serve as a test-bed for additional fusion power-plant technologies.

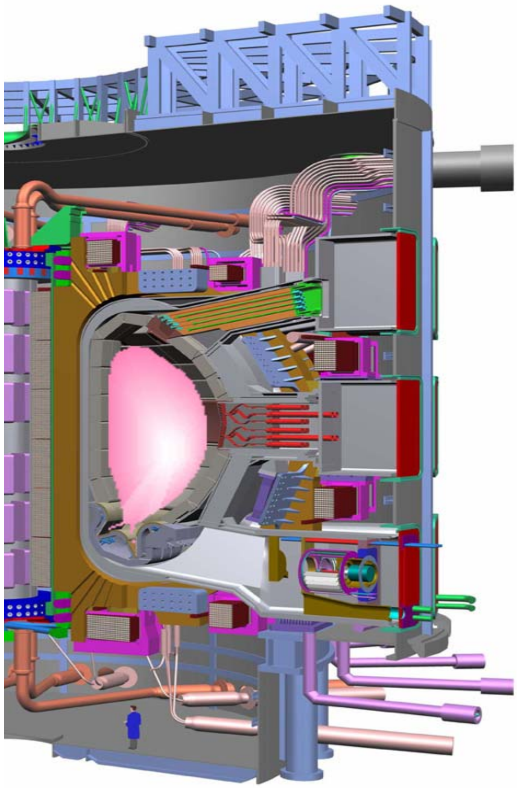


ITER

Applications: ITER is the next big step toward making fusion energy a reality. Fusion energy is particularly attractive as a future energy source because it is environmentally benign (it produces no air pollution and no carbon dioxide, and it does not create long-lived radioactive waste); its fuels are easily extracted from ordinary water and from lithium, an abundant element; and it can be generated on demand and in sufficient capacity to power large cities and industries.

ITER will make Critical Contributions in Each Area of Plasma Science

- Stability: Extend the understanding of pressure limits to much larger size plasmas, e.g., NTM meta-stability.
- Energetic particles: Study strong heating by fusion products, in new regimes where multiple instabilities can overlap.
- Turbulence: Extend the study of turbulent plasma transport to much larger plasmas, providing a strong test of gyro-Bohm physics.
- Plasma-materials: Extend the study of plasma-materials interactions to much higher power and much greater pulse length.

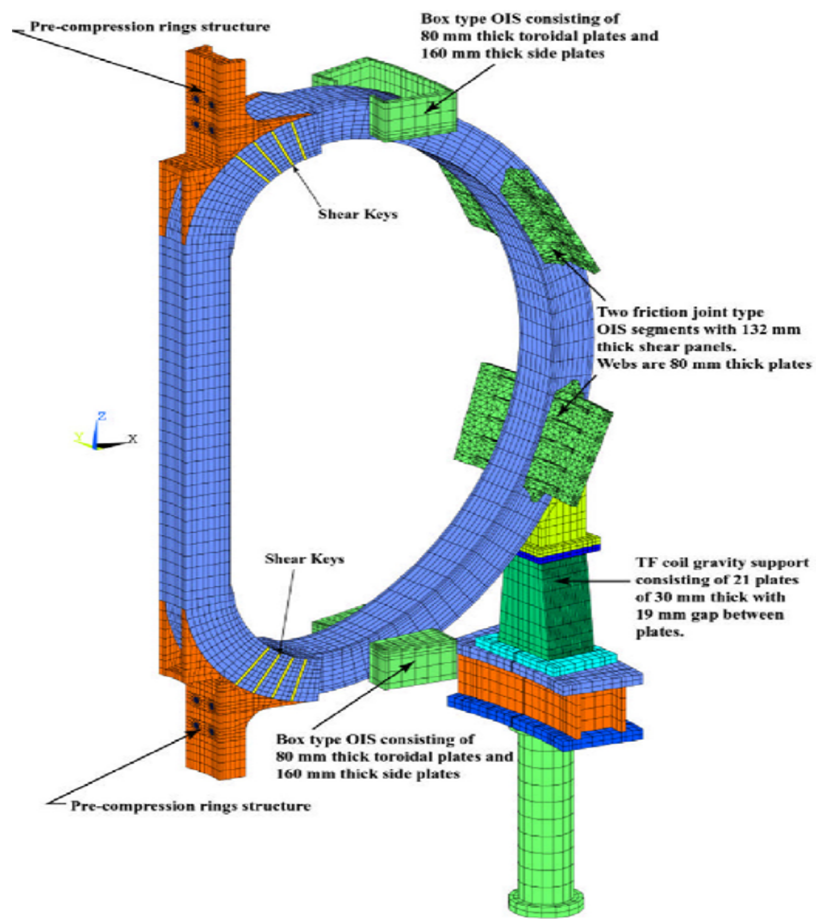


ITER Final Design

Today: 10 MW for 1 second, gain of < 1
ITER: 500 MW for 10 minutes, gain > 10
Power Plant: 2500 MW, continuous, gain > 25

ITER will Provide First Test of Major Fusion Technologies

- Superconducting Magnets
  - Power plant size and field, 40 GJ
- Plasma Facing Components
  - 5 MW/m^2 steady heat flux
  - 20% duty factor during operation
- Tritium Systems
  - Active recycling of tritium
  - Test of lithium blankets
- Heating and Current Drive
  - 50 MW continuous
  - 1 MeV neutral atoms,
    Ion Cyclotron, Electron Cyclotron



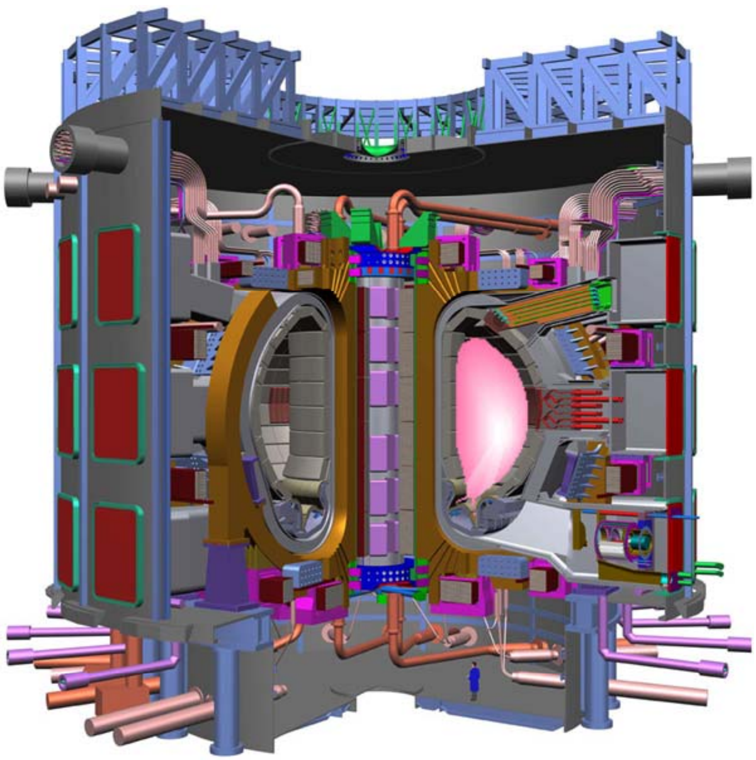
ITER toroidal field coil

ITER Negotiations:
Europe, Japan, Russia, US, China, South Korea

- Two sites are now on the table:
  - France: Cadarache, near Aix-en-Provence
  - Japan: Rokkasho, northeast corner of the main island

- The financial numbers add up:
  - The Host pays 50%
  - Each of the others pays 10%

- The key issues for resolution are:
  - Siting - how do we find a win/win?
  - Management of a major international construction project
  - Risk allocation



Site Selection Negotiations Continue

Rokkasho, Japan (northern Japan)

Cadarache, France, EU (southern France)

- **On November 8-9th, 2004, the Fourth Preparatory (Negotiations) Meeting for ITER Decision Making was held at Ray Orbach's level. All six ITER Parties were present.**

Common Message from 4th Preparatory Meeting for ITER Decision Making

(IAEA, November 8-9, 2004)

Delegations from China, European Union, Japan, the Republic of Korea, the Russian Federation, and the United States met at the IAEA headquarters in Vienna on 9th November 2004 to advance the ITER negotiations.

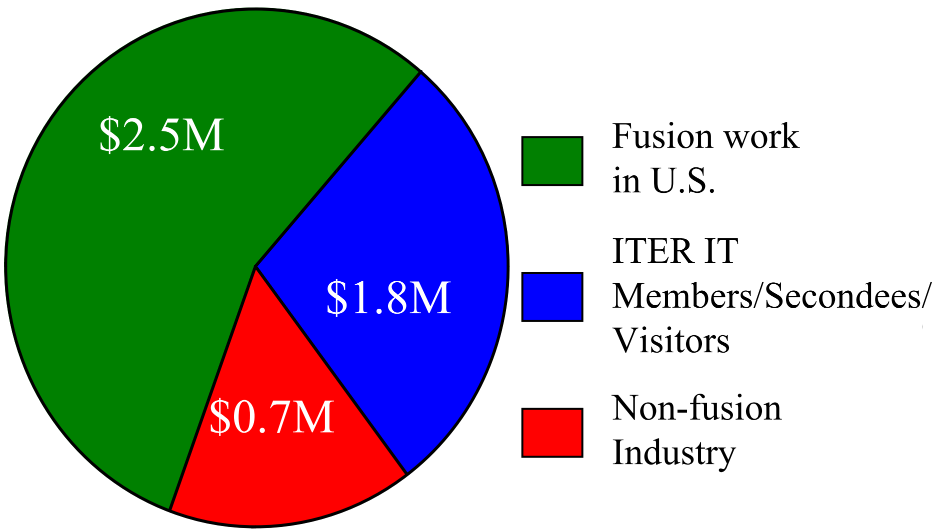
The two potential Host Parties, European Union and Japan, presented the results of recent intensive bilateral discussions on the balance of roles and the responsibilities of Host and non-Host in the joint realisation of ITER in the frame of a six-Party international co-operation. These discussions will continue in the near future with the aim of aligning the two Parties' views.

All Parties were greatly encouraged by the positive atmosphere and expressed their optimism that the process was now proceeding effectively towards a fruitful conclusion among the six Parties in the near future.

- **Resolution continues to be largely in the hands of the EU and JA.**

ITER Direct Funding for FY05

Distribution of Funding



Total of $5.0M in FY05

Specific Task Areas

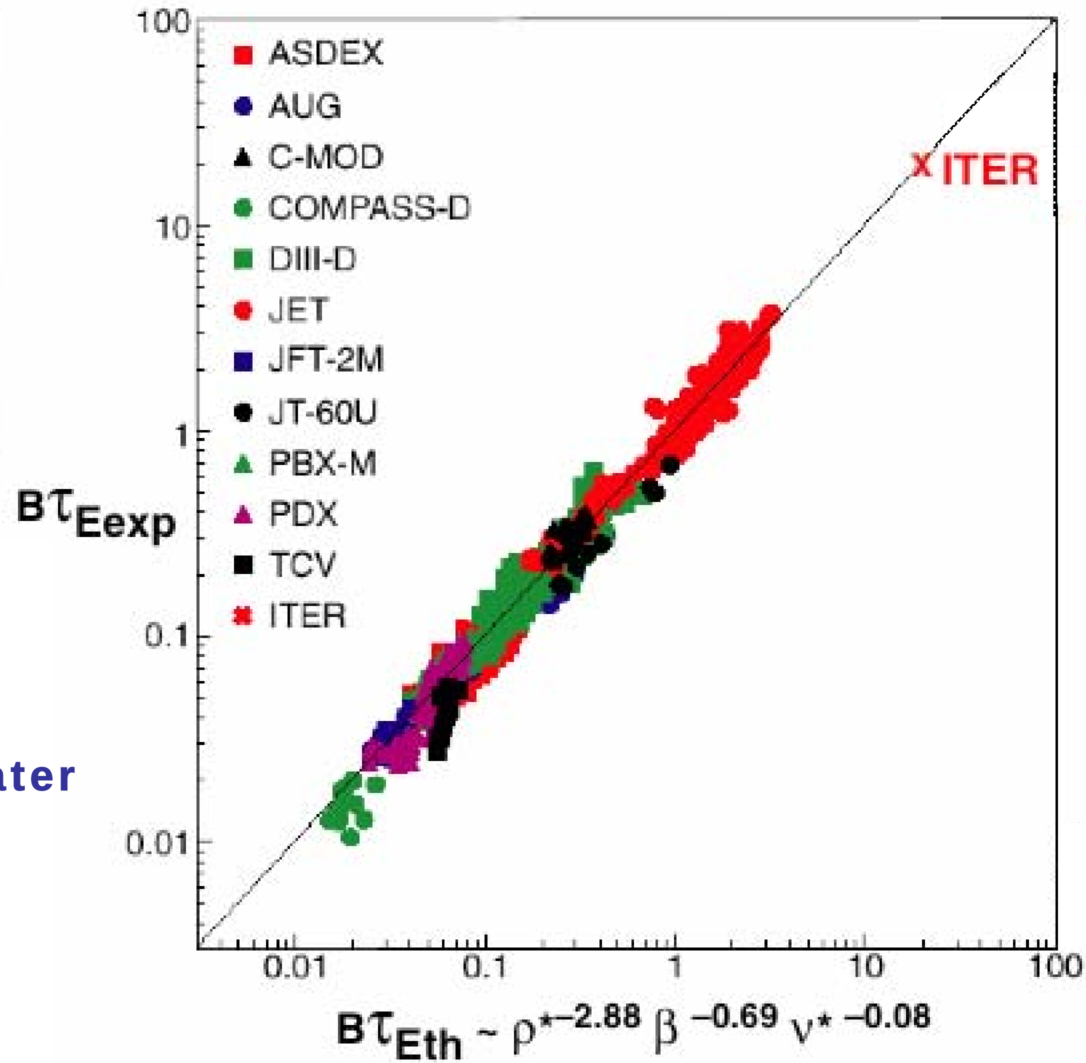
- o Magnet design and R&D
- o PFC design and R&D
- o Tritium processing design
- o Safety, power supplies, etc.
- o Project and procurement management

- o Magnets/PFC Secondees
- o ICH Visitors
- o Diagnostics Visitor

- o Strand qualification
- o Power Supply/Cooling water cost estimates

Experimentally Global Heat Confinement is Gyro-Bohm

Dimensionless Parameters
$\omega_c\tau = B\,\tau$
$\rho^* = \rho/\mathbf{a}$
$\nu^* = \nu_c/\nu_b$
β



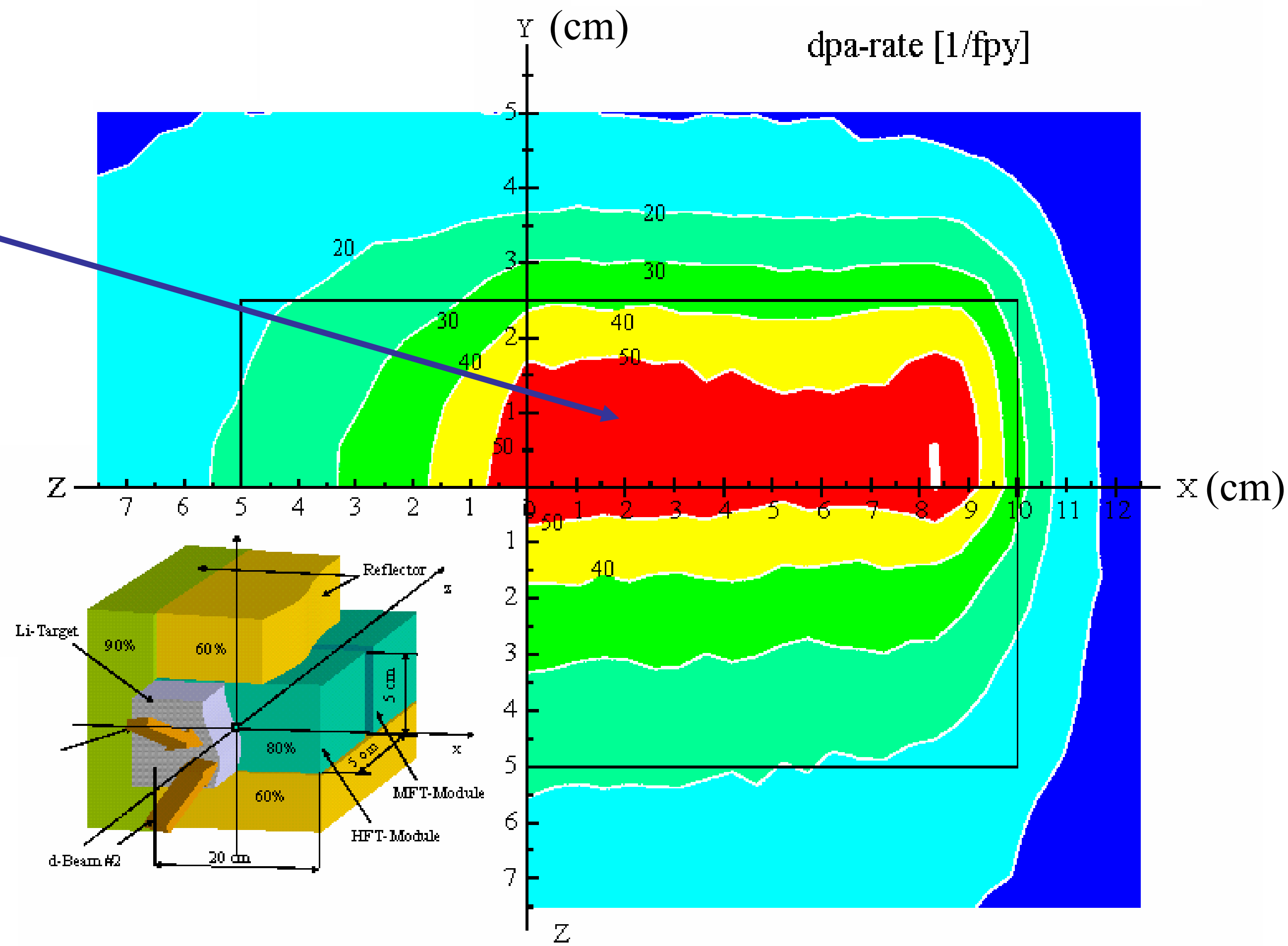
Design improvements and ongoing research give increasingly greater confidence in ITER performance

International Fusion Materials Irradiation Facility

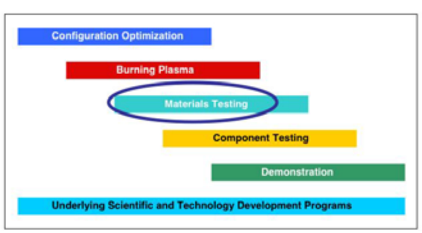
A D-Li stripping neutron source to test fusion materials at high fluence, realistic He/dpa ratios

1/4 of 5x20cm Target zone

Neutron Flux
~ 5 MW/m^2
~ 10x ITER

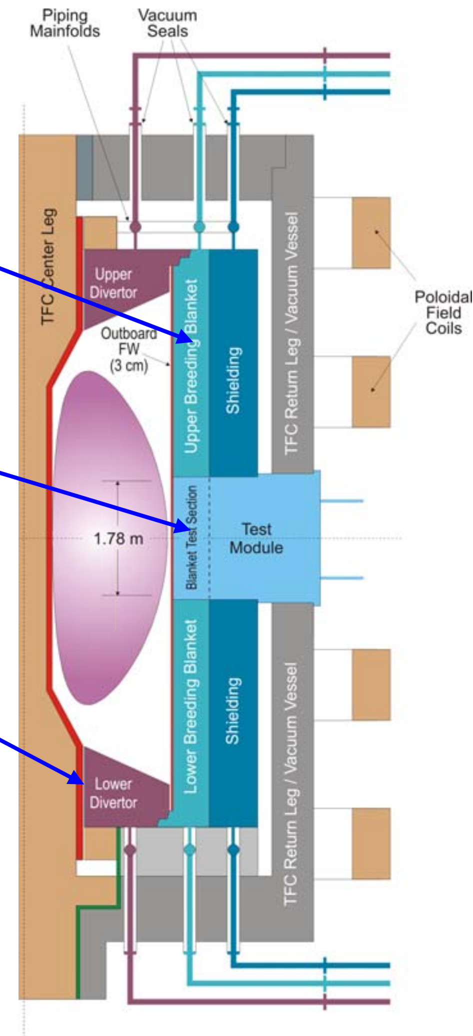


The Fusion Development Path is Defined by a Set of Overlapping Scientific and Technological Challenges

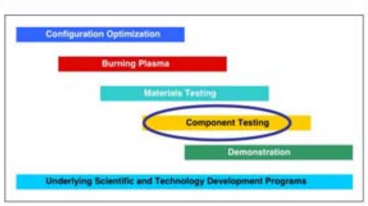


The Spherical Torus Leads to a Compact (R ~ 1.2m) High Fluence Component Test Facility

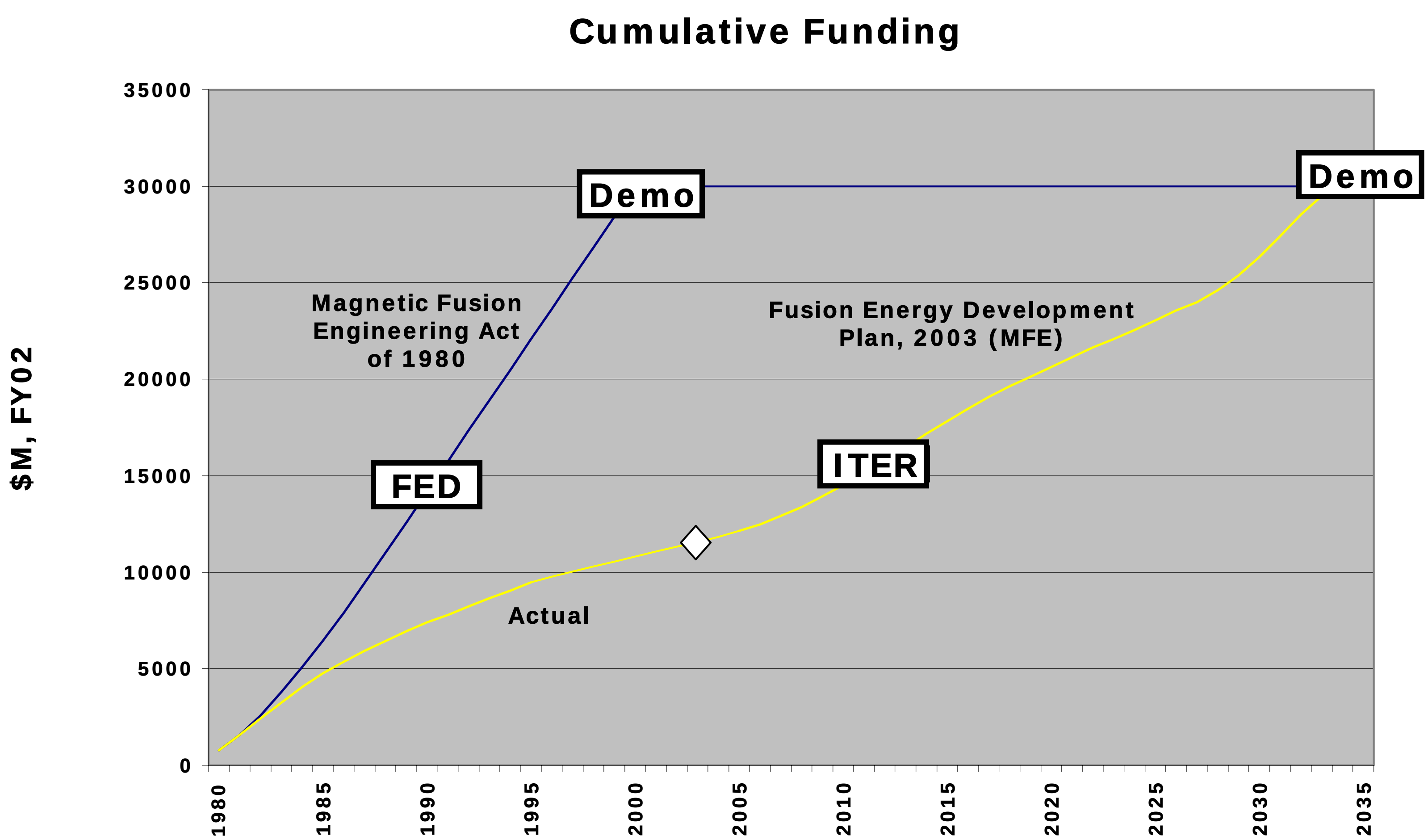
- Test blankets
  - Integrated assemblies removed vertically or as modules through mid-plane ports.
- Divertor
  - Integrated assemblies removed vertically, or through ports.
- A compact CTF can test components with available tritium
  - Demo will burn tritium at 140kg per full-power year
  - CTF will burn tritium at 4.5 kg per full-power year



The Fusion Development Path is Defined by a Set of Overlapping Scientific and Technological Challenges



The Estimated Development Cost for Fusion Energy is Essentially Unchanged since 1980



Fusion Research is Ready for a Burning Plasma Experiment

- Advances in diagnostics and computation have dramatically increased the understanding of high-temperature plasmas.
  - Basic scaling of ion turbulence well understood.
  - Ideal and resistive instabilities substantially understood.
- The fusion performance of ITER can be reasonably predicted.
  - ITER will contribute both to the fundamental scientific understanding of high-temperature plasmas and to the development of fusion energy.
- A viable development path for fusion energy can be defined, requiring both an international burning plasma experiment and healthy domestic research.
  - The projected cost of fusion energy development is unchanged.
- This is an exciting area of research and there are many linkages to other areas of science.

A final thought —Mankind has always derived inspiration from the stars (and in this case the Spitzer Space Telescope)